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An Assessment of Technical and Production Risks of Candidate Low-Cost Attitude / Heading Reference Systems (AHRS)

Daniel Yuchnovicz and Malcolm Burgess
Research Triangle Institute, Hampton, Virginia

William Hammers
Optimal Solutions, Wichita, Kansas

February 1999

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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EXECUTIVE SUMMARY

This report provides an assessment of technical and production risks of candidate low-cost attitude/heading reference systems. Included in this report is a discussion of low-cost Attitude and Heading Reference Systems (AHRS) under development, the characteristics of a low-cost AHRS, an analysis of the General Aviation (GA) market for low-cost AHRS, and an analysis of the risks associated with producing a low-cost AHRS in the anticipated volumes. This report was developed under NASA contract to aid the Advanced General Aviation Transport Experiments (AGATE) project management and participating avionics manufacturers and airframe manufacturers in understanding:

- the status of low-cost AHRS development,
- technical and certification issues / risks
- the estimated market demand, and,
- the production risk to manufacture low-cost AHRS in the volumes anticipated.

This report may also be useful to AGATE project management and member companies faced with the following decisions:

- possibility of NASA or the AGATE project further funding current NASA-sponsored low-cost AHRS developments;
- avionics manufacturers' assessment of market demand and decision to produce/not produce low-cost;
- low-cost AHRS developers' decision to start a production line or partner with a larger avionics manufacturer for production, and,
- airframe manufacturers' future planning of avionics offerings.

A detailed assessment of two candidate low-cost AHRS[1] currently being developed under the NASA SBIR program has shown that while technically feasible, there is some risk that the low-cost price goals may be difficult to achieve in the near term. This finding was attributable to the use of low-cost solid-state rate sensors where the challenge is reducing the noise and drift rates to levels where stable, certifiable performance can be achieved. Additionally, new and novel proprietary design approaches are utilized in the designs that increase the certification risk (more engineering hours expended) of gaining Federal Aviation Administration (FAA) Technical Standard Order (TSO) certification for a primary use AHRS. Since neither of the two developers have certified products in the market place, one way to reduce certification risk is for the developers to partner with larger, more experienced avionics manufacturers. This would provide access to additional engineering and certification expertise. The developers may still prove successful on their own, utilizing Designated Engineering Representatives (DERs) to

[1] D. Yuchnovicz, S. Law, and M. Burgess, *Attitude/Heading Reference System (AHRS) Risk Assessment Phase One*, Research Triangle Institute, Hampton, Virginia, December 1997.

provide the additional engineering and certification expertise that may be required to bring the low-cost AHRS to market.

A market analysis was performed for a low-cost AHRS in the GA market from 2001 to 2020. The following approach was used to develop the market assessment study:

1. A draft version of the AHRS market assessment study was sent to key avionics and airframe manufacturers for review and comment. They include
   - Four AGATE member airframe manufacturers
   - Two AGATE member avionics manufacturers
   - One non-AGATE avionics manufacturer.

   Each manufacturer has certified products in the GA market.

2. An interview was held with each manufacturer at their plant location to review the draft study and obtain feedback. In particular, the assumptions shown in Table 1 were reviewed for validity along with the cost model output.

Table 1. Assumptions

Assumption Item		Year	Value
1.	Optimistic number of FD aircraft	2020	20,000
2.	Most Likely number of FD aircraft	2020	10,000
3.	Pessimistic number of FD aircraft	2020	3,000
5.	Price of basic AHRS in the Retrofit Market (Excluding Certification Costs)	2001	$9,000
6.	Optimistic Price of AHRS	2020	$3,000
7.	Most Likely price of AHRS	2020	$5,000
8.	Pessimistic price of AHRS	2020	$7,000
9.	Cost of basic AHRS (Retrofit market) certification	2000	$1,000,000
10.	Cost of R&D for basic AHRS (Retrofit market) certification	2000	$1,000,000
13.	Cost of FD Aircraft AHRS (Future market)certification	2008	$1,000,000
14.	Cost of R&D for FD Aircraft AHRS (Future market) certification	2008	$500,000
15.	Start of New market Aircraft Production	2001	
16.	End of New market Aircraft Production	2015	
17.	Start of FD Aircraft (Future market) Production	2008	

Table 1. Assumptions (Concluded)

Assumption Item	Year	Value
18. Number of AHRS manufacturers	2000	4
19. Percent of Market FD Aircraft (Future market) captures from New market each year		12.5%
20. Variation in the New Aircraft market aircraft production		20%
22. Single Engine Piston fleet attrition until 2007		2.1%
23. Single Engine Piston fleet attrition after 2007		4.0%

3. An analysis was undertaken of the low-cost AHRS developers' business plans to determine production risk.

Two scenarios were analyzed in the assessment of the market for a low-cost AHRS:

- a baseline market consisting of the minimum number of aircraft incorporating a low-cost AHRS each year required to provide sufficient motivation to manufacture, and,
- an estimated reasonable profit expectation and return on the required investment based upon the probable number of aircraft incorporating a low-cost AHRS over this 20-year period.

The market for a low-cost AHRS depends upon its functionally. Three markets are anticipated which are defined as the Retrofit Aircraft, New Aircraft and Fully Digital (FD) Aircraft.

Based somewhat on the two SBIR low-cost AHRS developers' anticipated initial market offerings, a basic AHRS version was defined for a Retrofit market as a standalone (including a small display), secondary source of attitude and magnetic heading information. The buyers for the basic AHRS are current airplane owners who will retrofit it into their airplanes. A survey given to single engine airplane owners at the 1998 EAA annual air show in Oshkosh, WI, determined the probability-of-purchase distribution for the basic AHRS based upon projected price. The results show that 52 % would pay less than $2000 and 96% would pay less than $5000 for a basic AHRS. Further, the probability of purchase ranged from ≅ 0 at a cost of $9.6K, through 0.2% at $5.7K and breaking the 10% point at $3K. The probability of purchase increases exponentially with most respondents stating that their probability of purchase would be high if it cost as much as a hand-held GPS ($500 - $900).

The New Aircraft market consists of airplanes of new composite designs using 1990s technology including the Cirrus Design SR-20 and the Lancair Colombia 300 with Toyota and Honda to possibly follow. The New Aircraft AHRS would have improvements in functionality including certification as a primary source of attitude and heading and rate outputs to drive electronic displays (not included) and a 3-axis autopilot. The size of the New Aircraft market segment is expected to grow until the introduction of a FD Aircraft (defined as having a digital avionics databus to interconnect most if not all avionics) in 2008 and then slowly decline as the FD Aircraft gain market share. Production of the New Aircraft is estimated to stop being totally replaced by the Fully Digital Aircraft in 2015 due to the shift to all-digital avionics.

The FD Aircraft will make up the future market and will incorporate certified new and innovative cockpit displays that reduce training time and costs and substantially reduce the operational complexity. The introduction date of 2008 is a conservative estimate that reflects the combined risks of producing a certified low-cost AHRS capable of driving low-cost, intuitive primary flight guidance displays under development by the aviation industry[2]. The FD Aircraft will revitalize the GA industry through advanced avionics functionality, of which a low-cost AHRS is a key element. In addition to providing the usual attitude and heading information, the FD Aircraft AHRS must also provide position, velocity, rotational rates, and linear accelerations suitable for supporting the new and intuitive flight displays that will provide inertial flight path guidance, predictive guidance capabilities, etc.

Historical avionics price data collected from 1970 to 1990[3] was used to determine an expected price decay curve for the AHRS from 2001 through 2020. Based upon this analysis and current market conditions, the initial price of the basic AHRS for the Retrofit Aircraft market in 2001 is estimated to be $9,000[4]. This price represents a basic AHRS system installed in an existing airplane to provide for the display of a secondary source of attitude and heading. The most likely AHRS price decay curve falls from $9,000 in 2001 to $5,000[5] in 2020 while the AHRS was assumed to continue to increase in functionality, achieving the FD Aircraft AHRS capabilities.

The number of aircraft for which an AHRS is purchased each year in each market was used to determine the total number of AHRS sold each year. The AHRS numbers for the Retrofit, New and FD Aircraft markets were determined as follows:

- The number of aircraft for which a basic AHRS is purchased in the GA Retrofit Aircraft market was determined from the probability of purchase distribution (determined from the survey) and the number of aircraft in the Retrofit Aircraft market each year.
- The number of aircraft for which new AHRS is purchased in the New Aircraft market was estimated by using the probability of purchase distribution from the Retrofit Aircraft market and the number of New Aircraft produced each year over the period. Using the probability of purchase distribution from the Retrofit Aircraft market ensures a conservative estimate that has an empirical basis.
- The number of FD Aircraft for which an FD Aircraft AHRS is purchased was estimated to include all those aircraft produced.

[2] Several AGATE member avionics and airframe manufacturers described in-house advanced flight display development efforts for GA aircraft that follow the AGATE concepts, all requiring certified AHRS.
[3] RNAV systems were analyzed due to similar complexity and the span of historical pricing information available.
[4] Watson Industries anticipates the introduction of a certified AHRS in '99 at $10K while Archangel anticipates introduction of a certified AHRS in '99 at an undisclosed cost. The capabilities of these early applications is unknown.
[5] While in general agreement, some manufacturers feel that the price must decay to $3K by 2010.

- The total number of AHRS purchased each year then, is the sum of the Retrofit, New and FD Aircraft in the market.[6]

A minimum number of AHRS produced for New and FD Aircraft needed to return a net profit of 20% over the twenty-year period was determined after estimating[7]:

- Profit level of 25% without considering R&D and Certification costs
- R&D costs for the basic AHRS to be $1,000,000
- Certification cost for the basic AHRS to be $1,000,000
- R&D costs to increase functionality to FD Aircraft AHRS to be $500,000
- Certification cost for the FD Aircraft AHRS to be $1,000,000.

Based upon these assumptions the growth curve for production of the AHRS for New and FD Aircraft must climb to 3,000 units per year in 2020. Given the current activity to revitalize the GA industry, the growth in the number of new production aircraft should easily be achieved. This encouraging result is enhanced by the expectation of the break-even point at three years[8] and realization of positive profits through investment in the production of FD Aircraft AHRS.

The next step in the analysis was to estimate a reasonable profit based upon production targets set over the period of 2001 to 2020. This in turn yielded a reasonable return expected from the introduction of a basic AHRS through subsequent improvements to the FD Aircraft AHRS. Estimating a reasonable growth curve for production of general aviation aircraft involves uncertainty as does estimating a future price decay curve. A mathematical model was built to capture this uncertainty and incorporate it into the profit forecast. The forecasted profit over the 20-year period ranged from 21.54% to 23.06% with the nominal expected profit to be 22.5%[9].

In the last part of this study, production risk was determined by estimating the costs for a developer to either manufacture their design or for the developer to partner with an established avionics manufacturer to produce the design[10]. Interviews with the leading GA avionics and airframe manufacturers resulted in the following estimates:

- A start-up avionics company that has not ever manufactured a certified product could incur costs ranging from $6M to $12M[11]. This includes cost of capital equipment, personnel and certification of the production facilities. A manufacturer currently in the experimental aircraft market would probably encounter costs at the low end of this range.
- An established avionics company which makes products of similar complexity and function could start production for an estimated $0.25M to $0.75M.[12]

[6] The estimates are conservative in that they overlook redundancy requirements, spares requirements, etc.
[7] Avionics and airframe manufacturers generally affirmed Profit, R&D costs and Certification costs reflected in this report.
[8] Break even point is sensitive to the certification costs and the units produced per year.
[9] An 18% Return on Investment (ROI) is calculated at this profit range.
[10] Some avionics manufacturers expressed the opinion that they would prefer to partner early so as to participate in design that would help ensure certification.
[11] Estimates from a large GA avionics manufacturer was $6M - $8M and from a large GA airframe manufacturer was $8M-$12M.
[12] Estimate from a large GA avionics manufacturer.

The probability of a TSO-Certified, low-cost AHRS becoming available that is capable of supporting the New and Future Aircraft markets in the required time frame appears quite high. This reports concludes that the introductory price of a low-cost AHRS cannot far exceed $9K to be a viable product in the defined markets, and that the price must decay to at least the $3-$5K range with an increase in capability by the 2020 time frame.

The projected market for low-cost AHRS is estimated to be sufficient to provide the incentive for some manufacturers to enter the market and make a profit. For manufacturers entering the market for the long-term (through 2020), a profit of approximately 23% is estimated. However, depending upon the manufacturer's capabilities to produce an AHRS, the profit must be adjusted accordingly. The estimated profit of 23% is reasonably accurate for an established manufacturer making higher-cost AHRS and other similar products. The profit would have to be adjusted downward for other less capable manufacturers contemplating the production of a certified AHRS.

Several low-cost TSO-certified AHRS designs are projected to enter the market within the year, some supported by the NASA SBIR program, some from academia and others from industry alone. One of the NASA-sponsored AHRS development efforts appears poised to enter the production market in TSO-certified form in 1999 (Seagull Technologies, Inc.). At least two AHRS (Watson Industries AHRS-BA303 and Archangel AHRS) from the experimental aircraft market are expected to gain TSO-certification in 1999, one with a projected single unit price of about $10K. Several promising designs are also on the horizon which might require venture capital or other similar funding or partnering with established manufacturers to bring the certified AHRS to market (Vision Micro Design, Orion Dynamics and Control, and EPSCoR (Kansas State University)).

1. Introduction

This report provides an assessment of technical and production risks of candidate low-cost attitude/heading reference systems. Included in this report are a summary of two low-cost Attitude and Heading Reference Systems (AHRS) under development, an analysis of the General Aviation (GA) market for low-cost AHRS, and an analysis of the risks associated with producing a low-cost AHRS in the anticipated volumes. This report can aid the Advanced General Aviation Transport Experiments (AGATE) Program, management and participating avionics manufacturers and airframe manufacturers in understanding:

- the status of low-cost AHRS development,
- the market demand, and,
- production risk,

so that informed programmatic and business decisions can be made.

These decisions may include:

- possibility of NASA / AGATE Program further funding of NASA-sponsored low-cost AHRS developments currently on-going;
- manufacturers' assessment of market demand and decision to produce/not produce low-cost AHRS of a certain capability;
- manufacturers' decision to start a production line for low-cost AHRS or license the design to a larger manufacturer, and/or
- airframe manufacturers' future planning of avionics offerings.

1.1 Background

Two major partnerships, the AGATE Program and the General Aviation Propulsion (GAP) program, were developed by the National Aeronautics and Space Administration (NASA) to explore and advance the technologies needed for future personal air transportation systems. Goals of these partnerships include the definition of the operating requirements for a personal air transportation system that meets the public's expectations.

The AGATE Program is a unique government-industry-university partnership developed by NASA to support revitalization of the U.S. general aviation industry. It was initiated in 1994 to produce the design guidelines, industry standards and certification methods for aircraft, flight training systems, and airspace infrastructure for next generation single pilot, 4-6 place, near all-weather light planes. These advanced aircraft will use advanced flight guidance displays that allow low-time pilots to fly safely and reduce the training burden of maintaining instrument currency.

A low-cost AHRS is a key element of the advanced aircraft and is required to provide aircraft state information that is used by the advanced flight guidance displays. While the concept of an AHRS is not new, an AHRS capable of providing the outputs needed to support advanced flight displays can cost from tens of thousands of dollars in aircraft certificated to Federal Aviation Regulation (FAR) Part 25. In addition to the usual attitude and heading information provided by a basic AHRS, the AHRS required in AGATE airplanes must provide velocity, rotational rates, and accelerations suitable for supporting new and intuitive flight displays that will provide inertial flight path guidance, predictive guidance capabilities, etc. Current costs for AHRS providing these functions places them out of the price range for the GA market segment under consideration. Therefore, the introduction of a low-cost AHRS certified for use in aircraft certificated in accordance with Federal Aviation Regulation (FAR) Part 23 is critical to the AGATE Program and airframe manufacturers who want to incorporate advanced flight displays at the earliest opportunity.

1.2 Scope

This report addresses the second phase of a two phase effort. The first phase focused on the technical evaluation of two candidate low-cost AHRS under development via the sponsorship of the NASA SBIR program.[13] This second phase report:

- briefly summarizes the findings in the phase one report;
- provides an estimate of the market volume for this low-cost AHRS based upon models for market price and projected aircraft demand, and,
- provides estimate of the production risk that a developer may encounter when bringing a certified AHRS into production.

2. Technical Risk Assessment Summary

A detailed technical, schedule and certification risk assessment of two candidate AHRS was performed in the first phase of this two-phase study. These two on-going AHRS development programs have received NASA funding and were the subjected of analyses to determine the risks of bringing a certified product to market. The analysis included:

a) determining the functions and measured / predicted performance anticipated;
b) a Functional Hazards Analysis (FHA) to assess the assurance levels for hardware and software for the loss of a function or when a function produces hazardous/misleading data;
c) a Failure Modes and Effects Analysis (FMEA) to determine the consequence of component failures on the functions provided, and,
d) an assessment of the technical, schedule and certification risks.

The results of the technical analyses are proprietary to the individual companies and are not described here. Instead, a technical description of similar design concepts and the problems / risks associated with these designs is provided that will allow the reader to understand the technical issues without revealing proprietary information.

2.1 AHRS Overview

2.1.1 Technical Summary

An AHRS is a self-contained system that provides an attitude and heading reference for on-board systems including primary flight displays and autopilots. To be a viable product for the AGATE aircraft and other airframe manufacturers wishing to incorporate

[13] D. Yuchnovicz, S. Law, and M. Burgess, *Attitude/Heading Reference System (AHRS) Risk Assessment Phase One*, Research Triangle Institute, Hampton, Virginia, December 1997.

advanced flight displays and 3 and 4-axis autopilots, the AHRS should ideally provide the following features:

- Attitude, component velocities and accelerations
- High relative and absolute accuracies (at least those of a vertical and directional gyro)
- Acceptable real-time response in high-dynamic environments
- Unaffected by environment
- Integrity monitoring
- High reliability
- Compatibility with avionics suite requirements
- Affordability to the GA market

These characteristics are achievable using “strapdown” inertial measuring devices that have all solid state circuitry. Instead of measuring the motion of the aircraft around a gimbaled, spinning mass gyro, the output of solid-state rate sensors (also called rate gyros) which are affixed to the airframe are integrated to provide an angular measurement of aircraft motion. Strapdown systems essentially have “mathematical gimbals” in which the aircraft angular rates are measured and the attitude angles calculated . The advent of accurate solid-state rate sensors and powerful microprocessors have made strapdown AHRS possible. Solid state circuitry affords reliability much greater than spinning mass gyros (on the order of 50,000 hours versus 2,000 hours).

2.1.2 Sources of Error - High Drift Rate Sensors

Most of the design difficulty in the development of a conventional low-cost strapdown AHRS can be traced to the performance of the low-cost solid-state rate sensors. These devices are typically mounted along each of the three body axis of the aircraft to provide angular rate sensing along each axis. The outputs are sensed and integrated over time to provide the absolute angular position relative to local level. There are several design issues. First is that of quality versus cost. Low cost solid-state rate sensors exhibit low accuracy and noisy outputs. These and other factors result in an excessive drift rate or bias over time, i.e. the rate sensor appears to drift or precess. Absolute pitch and roll angles become increasingly inaccurate due to the angular rate integrations including the drift error component. Therefore, minimizing drift or bias is necessary in order to maintain an absolute measurement of attitude.

Drift rates can be excessive in very low-cost rate gyros, and on the order of 400 degrees per hour. High precision spinning mass gyros can provide drift rates of less than 0.0001 degrees per hour[14], but are cost prohibitive in all but the most costly aircraft. If a very low-cost rate gyro is initialized in a level orientation, it's integrated output could appear to precess at over 6 degrees per minute, causing the attitude indication to be as much as 90 degrees off within 15 minutes. These errors are independent of aircraft motion and Earth rate. A major challenge then is to reduce the noise and drift while achieving TSO-required accuracy at affordable cost.

[14] S. Merhav, *Aerospace Sensor Systems and Applications*, Springer,-Verlag, New York, Inc., 1996, pg. 261

2.1.3 Approaches to Reducing the Error Effects of Drift Rate

Several published approaches are used to reduce drift, including high-cost solid-state gyros such as ring laser gyros, or to measure attitude directly from the GPS satellite. A vertical reference mechanism is used to maintain knowledge of local level from which the aircraft body angles are measured. Several mechanisms for accomplishing this are well documented in the public domain[15]. The vertical reference is typically the Earth's gravity vector. One AHRS for example[16], includes pitch and roll axis pendulums (or accelerometers) to sense the direction of the gravity vector and accelerations due to aircraft motion. The attitude and heading derived by integrating output from the solid-state rate gyros is compared with the two vertical reference pendulums and a triaxial magnetometer to derive short term absolute errors. These errors are filtered (using a Kalman filter) over a long time constant and are used to adjust biases in the system so that the long-term convergence of the system is to the vertical reference (gravity) and the magnetic heading.

The bias of the vertical reference due to centrifugal force and changes in forward acceleration must be removed, e.g. during a long turn the vertical roll-axis pendulum would include a horizontal acceleration component as well as the gravity component, thus registering a local level close to the current angle of bank. Compensation for the effect of this centrifugal force (actually the centripetal acceleration) is based on calculating the horizontal turn rate and multiplying it by the aircraft's forward velocity to derive the radial acceleration component. The result is subtracted from the vertical reference pendulum for the roll axis. The compensation for the aircraft's forward acceleration is based on the changes in average forward velocity. The result is subtracted from the vertical reference pendulum for the pitch axis. Note that in this AHRS and others, the velocity is typically input to the AHRS from an air data sensor or GPS.

Additionally, short term blanking circuits can be used to switch off the error correction of the vertical reference during highly dynamic, high-g maneuvers, thus preventing the vertical reference from accumulating the acceleration bias. Blanking may occur when pitch or roll angles exceed 45 degrees, or when measured acceleration exceeds some predetermined g value.

In the complete absence of the vertical reference compensation mechanisms described above, accurate attitude would be available from the low-cost rate gyros for only about two minutes before becoming hazardously misleading due an uncorrected drift rate of about 100 degrees per hour for this AHRS. In normal attitudes, error is corrected with a 15-second time constant. Loss of the velocity input used in error correction of the vertical pendulum references reduces the absolute accuracy, but converges over time to the vertical but at a lower accuracy, similar to a common spinning mass vertical gyro.

As mentioned, this AHRS relies on an external velocity input to correct the vertical reference. Other methods are available including the use of GPS aiding[17] to help

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[15] R.P.G Collinson, *Introduction to Avionics*, Chapman & Hall, London, UK, pgs. 223 - 245

[16] Watson Industries, Inc. AHRS-BA303. This AHRS was not the subject AHRS analyzed in the Phase I report, but is useful to illustrate the types of issues that must be dealt with in this report.

[17] S. Merhav*, Aerospace Sensor Systems and Applications*, Springer,-Verlag, New York, Inc., 1996, pgs 395 - 439

maintain the vertical reference. Each of these methods presents special certification challenges in that the system must still provide minimum acceptable performance during the loss of the external reference, i.e. the vertical reference must be self erecting, i.e. seek the gravity vector over time if it is to remain the primary source of attitude during the loss of the external reference. Implementations which rely on GPS or other external systems must be designed to have either reversionary modes or reliable methods to notify the pilot/avionics to use a dissimilar source of attitude and heading until GPS is again available.

Ideally, the AHRS should be able to detect that the output is degrading and notify the pilot / avionics system. This capability is specified for developers of FAR Part 25 AHRS where the switch-over to a built-in secondary system within the same AHRS is provided automatically with pilot notification[18]. While a basic AHRS provides attitude and heading outputs in a digital format, more sophisticated systems can also provide body angular rates, component velocities, and component acceleration information among others. A full complement of outputs are available from high-end AHRS[19]. The AHRS functions thought to satisfy each of these markets were defined for the basic, New and Fully Digital (FD) Aircraft AHRS respectively and are shown in Table 2.1.3-1. The anticipated use of each function is also shown.

Table 2.1.3-1. AHRS Functionality for the Retrofit, New and Future Aircraft Markets

AHRS Function	B	New	FDA
Pitch Angle	x	x	x
Roll Angle	x	x	x
Magnetic Heading	x	x	x
True Heading		x	x
Yaw Rate (Instantaneous Rate) *(AP)*		x	x
Roll Rate (Instantaneous Rate) (*AP)*		x	x
Pitch Rate (Instantaneous Rate) (*AP)*		x	x
Velocity North (*FPM)*			x
Velocity East (*FPM)*			x
Velocity Vertical (*FPM)*			x
Acceleration North *(P)*			x
Acceleration East *(P)*			x
Acceleration Vertical *(P)*			x
Acceleration Body Longitude (*AT)*			x
Acceleration Body Latitude (*AT)*			x
Acceleration Body Normal (*AT)*			x
B - basic AHRS Functions for the Retrofit Aircraft market, New – New Aircraft AHRS for the Anew Aircraft market, FDA – FD Aircraft AHRS for the FD Aircraft market, AP - Required for Autopilot, AT - Required for Auto Throttle, FPM - Required for Flight Path Vector, P - Predictive Displays			

[18] ARINC 705-5 AHRS, para. 1.2.1 Modes of Vertical Operation
[19] ARINC 705-5 AHRS, para. 4.31. Digital Data Outputs

2.2 Technical Risk Summary

The major technical risks faced by any developer of a solid-state AHRS are as follows:

- Ability to use low-cost angular rate sensors and still meet cost and performance goals in a FAA TSO-certified design.
- Use of any external sensor input to aid in vertical reference correction and meet certification standards when external sensor is lost. Requires reversionary system or self-erecting vertical reference.
- Dependence on any form of GPS sensing for aiding, velocity inputs or other information and meet TSO performance standards when GPS is lost.
- During development stage, risk that the contemplated use of a promising angular rate sensor or other technology will not be allowed by the manufacturer for reasons of perceived liability exposure.
- Ability to develop software to the assurance levels set in RTCA DO-178B.
- Ability of the developer to meet the environmental requirements in applicable portions of RTCA DO-160C/D per the applicable TSOs required for certification.

3. AHRS Market Assessment

This section of the report provides an estimate of the market volume for a low-cost AHRS based upon models for market price and projected aircraft demand. The total market consists of the following three market segments: Retrofit into existing general aviation aircraft, installation into New single engine piston (SEP) aircraft, and incorporation into the future Fully Digital (FD) aircraft. These three market segments are further defined as follows:[20]

- Retrofit Aircraft Market - Existing airplanes that could benefit from a standalone, secondary source of attitude and magnetic heading information.
- New Aircraft Market - Airplanes of new design using 1990s technology.
- FD Aircraft Market – Airplanes having a digital avionics data bus to interconnect most if not all avionics. These airplanes will incorporate novel new and innovative cockpit displays that reduce training time and costs and substantially reduce the operational complexity.

The time frame of this study is from the year 2001 through the year 2020. This window was chosen to accommodate the estimated time to bring the basic AHRS to market.

The following approach was used to develop the marketing assessment study. The assumptions made in the market assessment model are presented in Section 3.7.

1. A draft version of the AHRS market assessment study was sent to key avionics and airframe manufacturers for review and comment. They include
   - Four AGATE member airframe manufacturers
   - Two AGATE member avionics manufacturers
   - One non-AGATE avionics manufacturer

[20] Additional information may be found in AHRS Market Description, Configuration and Performance Summary, Research Triangle Institute, July 22, 1998, Malcolm A. Burgess, Daniel E. Yuchnovicz.

Each manufacturer has certified products in the GA market.

2. An interview was held with each manufacturer at their plant location to review the draft study and obtain feedback. In particular, the assumptions were reviewed for validity along with the cost model output.

3. An assessment of the possible production methods was made along with an analysis of the low-cost developers business plan to determine production risk.

3.1 AHRS for General Aviation Aircraft

The cost of an AHRS for the GA market must be significantly reduced from today's cost which begin at approximately $20,000 and can go much higher. Some cost reduction will be obtained through continued advancement in avionics technology and certification costs reduced by the AGATE project initiatives, but these alone will not be enough to meet this goal. Additional cost reductions must be obtained through the economies-of-scale that can only be achieved by retrofitting a basic AHRS into a portion of the existing fleet of GA aircraft. The basic AHRS could be useful as a secondary source of attitude and heading information in any aircraft, especially those used for regular flight[21]. But if economies of scale are possible in the near term, it will be primarily because of AHRS retrofits in single engine piston (SEP) aircraft. This is dictated by the size of this segment compared to other segments of the general aviation fleet.

The existing GA fleet consists of approximately 187,000 aircraft[22], with SEP aircraft comprising 72.2% of this fleet. Piston twins are only 8%, while turboprops and turbojets together are just 5%. Consequently, an accurate projection of the size of the single-engine segment of the retrofit market is critical for determining what AHRS production levels can be achieved. After making this projection, an estimate of the size of the AHRS retrofit market is determined by using a historical analysis of the acceptance and growth of RNAV installations and through the analysis of actual surveys of SEP/GA aircraft owners[23].

3.1.1 Historical Growth

Table 3.1-1 was constructed to determine the maximum rates of annual and sustained growth in SEP production since 1960. This was done to provide historical support for the large growth rates necessary to reach 20,000[24] FD Aircraft units per year by 2020 with production starting in 2008. The compound annual growth needed to get from the 905 SEP units actually delivered in 1997 to 20,000 units in 2020 is 14.41%.

[21] The consensus of the manufacturers interviewed was that the basic AHRS must be certified as a primary system in order to be generally accepted by the marketplace.
[22] See Appendix A
[23] See Appendix B
[24] In this analysis, 20,000 aircraft is the optimistic estimate for the number of aircraft produced in 2020.

Table 3.1-1. Past Deliveries

ANNUAL NEW AIRCRAFT DELIVERIES				
YEAR	TOTAL USA	ANNUAL GROWTH TOTAL (%)	SE USA	ANNUAL GROWTH SE (%)
1960				
1961				
1962	6,697		5,690	
1963	7,569	13.02	6,248	9.81
1964	9,336	23.35	7,718	23.53
1965	11,852	26.95	9,873	27.92
1966	15,768	33.04	13,250	34.20
1967	13,577	(13.90)	11,587	(12.55)
1968	13,698	0.89	11,398	(1.63)
1969	12,457	(9.06)	10,054	(11.79)
1970	7,292	(41.46)	5,942	(40.90)
1971	7,466	2.39	6,287	5.81
1972	9,774	30.91	7,913	25.86
1973	13,646	39.62	10,788	36.33
1974	14,166	3.81	11,579	7.33
1975	14,056	(0.78)	11,441	(1.19)
1976	15,451	9.92	12,785	11.75
1977	16,904	9.40	14,054	9.93
1978	17,811	5.37	14,398	2.45
1979	17,048	(4.28)	13,286	(7.72)
1980	11,877	(30.33)	8,640	(34.97)
1981	9,457	(20.38)	6,608	(23.52)
1982	4,266	(54.89)	2,871	(56.55)
1983	2,691	(36.92)	1,811	(36.92)
1984	2,431	(9.66)	1,620	(10.55)
1985	2,029	(16.54)	1,370	(15.43)
1986	1,495	(26.32)	985	(28.10)
1987	1,085	(27.42)	613	(37.77)
1988	1,143	5.35	628	2.45
1989	1,535	34.30	1,023	62.90
1990	1,144	(25.47)	608	(40.57)
1991	1,021	(10.75)	564	(7.24)
1992	941	(7.84)	552	(2.13)
1993	964	2.44	516	(6.52)
1994	928	(3.73)	444	(13.95)
1995	1,077	16.06	515	15.99
1996	1,130	4.92	530	2.91
1997			905	70.75
TOTAL	269,782		215,094	

The first column in Table 3.1-1 is the delivery year followed by the total United States deliveries in column 2. The deliveries annual growth percent is in column 3 and column 4 and 5 give similar information for single engine deliveries.

The historical data indicate that these growth rates are well within the industry's capabilities. For SEP airplanes, the simple average of growth in positive growth years has been a surprising 21.9%. This highlights the opportunistic nature of the industry to sell all it can in good-times.

Naturally, good times like these don't last. The maximum number of continuous positive growth years is 4.

The average (compounded) annual growth for SEP production during GA's golden years (1971 - 1978) was 11.7%. Variations in demand affected these results, however, and they should not be interpreted as a maximum sustainable growth rate for GA's production facilities. Indeed, growth rates as high as 28.5% were sustained for 3 years from 1964 through 1966. This high growth was sustained even though nothing revolutionary, like an aircraft with FD Aircraft technologies, was introduced during any of these years. With the introduction of such airplanes, however; very high, sustained demand is presumed likely, and the industry's history shows that it should be able to keep up with this growth.

In addition to growth, it is necessary to select the first year's unit production for each New Aircraft and FD Aircraft model. Again, historical production information is used as a starting point. Table 3.1.1-2 looks into the history of Cessna Aircraft's first year deliveries for all-new SEP models introduced in the 1950s and 1960s. These years were chosen because later single-engine model introductions were derivative models (mostly retractable gear and powerplant variations). A reasonable estimate of the upper bound of the first year production for each New/FD Aircraft model is the average of the Cessna data. Production will likely be constrained entirely by production considerations, rather than demand; so this historical average of the most Cessna could produce, which was approximately 400 units in the first year, is a credible starting point.

Table 3.1.1-2. Initial Rates

FIRST YEAR PRODUCTION
FOR ALL-NEW SE MODELS
(1951 & 0N)

YEAR	MODEL	UNITS
1953	180	664
1955	172	173
1956	182	983
1958	175	702
1958	150	122
1959	210	43
1962	205	165
1963	206	61
1967	177	557
	Average	386

If one estimates, the number of FD Aircraft manufacturers at four, with at least one of these being companies formed after 1980, it is possible to meet projected first year production levels. If we assume that the new company's first year production rate is only fifty percent of the more experienced manufacturers, then a reasonable upper bound for the total first year's production of FD Aircraft is still 1,400 units [(400)(3) + (200)*(1)].

3.2 Attrition of 1996 Aircraft Fleet Through 2020

Airplanes have a much longer and more varied life than automobiles, with which people have some familiarity. The attrition rate for cars is roughly 18% annually, so that in 10 years, only 13.7% are left on the road.

One approach for estimating airplane attrition is to take production data over a period of time and follow it's effect on the actual active fleet size reported by the FAA. This is done in Table 3.2-1 for the period 1962 to 1996[25]. An adjustment is made for the fact that some airplanes (about one-third) are initially sold overseas, but no adjustment is made for foreign planes imported to the USA (less than 100 per year in recent years). In this case, the attrition numbers account for airplanes that are wiped out in accidents, airplanes removed from service (but usually not junked), and the export of used airplanes.

The airplanes removed from service amount to a large inventory that comes in and out of the fleet from year to year. Consequently, some years show negative attrition. This large inventory of usable but inactive airplanes represents a huge inertial effect in the demand equation that damps the effects of demand on new airplane sales and confounds estimates of growth.

Table 3.2-1. Historical Attrition

YEAR	TOTAL US DELIVERIES	PROJECTED SE FLEET w/o attrit.	REGISTERED SE FLEET	SE ATTRIT. (UNITS)	SE ATTRIT. (%)
1960			68,040		
1961			71,010		
1962	4,552	75,562	73,456	2,106	3.0
1963	4,998	78,454	73,626	4,828	6.6
1964	6,174	79,800	76,136	3,664	5.0
1965	7,938	84,074	81,134	2,940	3.9
1966	10,812	91,946	88,621	3,325	4.1
1967	8,992	97,613	96,471	1,142	1.3
1968	9,061	105,532	103,735	1,797	1.9
1969	7,933	111,668	108,604	3,064	3.0
1970	4,171	112,775	109,492	3,283	3.0
1971	4,728	114,220	109,100	5,120	4.7
1972	6,085	115,185	120,364	(5,179)	-4.7
1973	7,994	128,358	126,074	2,284	1.9
1974	8,105	134,179	131,512	2,667	2.1
1975	8,581	140,093	136,639	3,454	2.6
1976	9,857	146,496	144,752	1,744	1.3
1977	11,046	155,798	149,300	6,498	4.5
1978	11,475	160,775	160,651	124	0.1
1979	10,177	170,828	168,390	2,438	1.5
1980	6,057	174,447	168,435	6,012	3.6
1981	5,022	173,457	167,898	5,559	3.3
1982	2,090	169,988	164,173	5,815	3.5
1983	1,465	165,638	166,247	(609)	-0.4
1984	1,398	167,645	171,922	(4,277)	-2.6
1985	1,132	173,054	164,385	8,669	5.0
1986	694	165,079	171,777	(6,698)	-4.1
1987	365	172,142	171,035	1,107	0.6
1988	394	171,429	164,760	6,669	3.9
1989	646	165,406	170,370	(4,964)	-3.0
1990	365	170,735	165,073	5,662	3.3
1991	353	165,426	154,102	11,324	6.9
1992	337	154,439	143,580	10,859	7.0
1993	329	143,909	130,687	13,222	9.2
1994	312	130,999	123,332	7,667	5.9
1995	364	123,696	128,804	(5,108)	-4.1
1996	368	129,172	135,244	(6,072)	-4.7

[25] Sources: (1)GAMA 1997 Statistical Data Book, (2) Reports From GAMA & Worldwide Sales, (3) FAA Data (Blue Printout), (4) Business Aviation Annual Sales Summaries

These results show an average attrition of 2.1%, with values ranging from 9.2% in 1993 to -4.7% in 1996. Keep in mind, however, that recent FAA data is subject to revisions, so it is best not to focus on the 1995 or 1996 data or to analyze this recent data too closely.

A piecewise analysis of attrition for each major period of the past several decades gives the surprising result that attrition is low in bad times and high in good times. It was expected that people would park the old planes in bad times and bring them out in good times but it appears that they just stop buying new planes in bad times and put the old ones back into service.

The annual attrition rates in Table 3.2-2 are considered to be appropriate for projections over the long haul. The most likely attrition rate is simply the historical average attrition of 2.1%. Note that at this rate the fleet half-life is 33 years, and it reaches 13.7% (the % of automobiles remaining in 10 years) in 93 years. The 4.0% maximum attrition was selected to give a fleet half-life of 17 years, or half the half-life for the most likely value; and this maximum attrition reaches 13.7% fleet size in 49 years. The minimum attrition rate of 1.8% is based on insurance data for actual permanent removals of popular airplanes from the fleet due to non-repairable damage.

Table 3.2-2. Attrition Levels

SE Airplane Attrition Rates			
	Attrition Rate	Fleet Half Life	Fleet 13.7% Life
Minimum	1.80%	38 yr	109 yr
Most Likely	2.10%	33 yr	93 yr
Maximum	4.00%	17 yr	49 yr

Table 3.2-1 indicates that it might be instructive to break the period 1962 -1996 into four intervals: 1962 - 1971, 1972-1979, 1980-1989, and 1990-1994. Table 3.2-3 divides the attrition statistics from 1962-1994 into these four intervals. Each of the intervals in Table 3.2-3 show a marked difference from those before and after. However, the chosen intervals illustrate the earlier observation that attrition is lower in bad times and higher in good times.

Table 3.2-3. Period Attrition

YEARS	ANNUAL ATTRITION
1962 - 1971	3.51%
1972 - 1979	1.33%
1980 - 1989	0.99%
1990 - 1994	6.48%

Given the above analysis and as shown in Figure 3.2-1, it is reasonable to assume that attrition of the 1996 fleet marches along at 2.1% for the years 1997 - 2007 and then increases to 4% as the FD Aircraft are introduced and holds this rate through 2020. Under these conditions, the 1997 fleet of 133,000 aircraft is reduced through attrition to 67,000 aircraft in 2020.

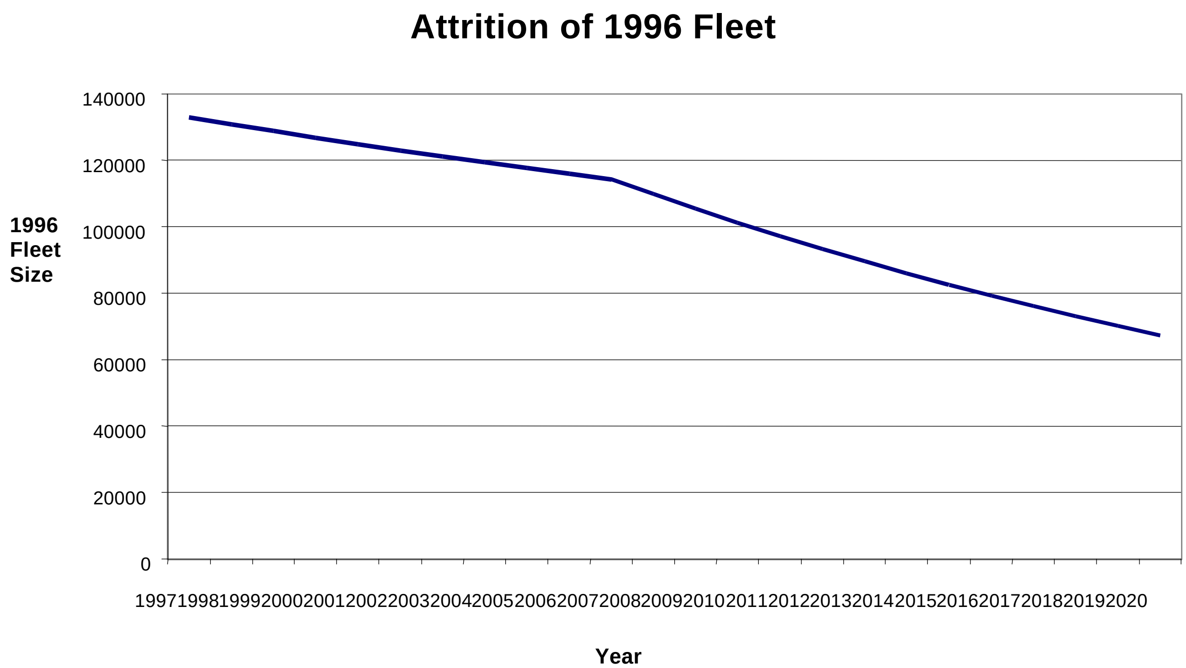

Figure 3.2-1. Attrition of Fleet

3.3 Determining of Number of New and Fully Digital Aircraft

New GA aircraft production is expected to exceed 2,000 units by the year 2001 and increase for the next eight years until the anticipated introduction of the FD Aircraft. It will then lose market share to the FD Aircraft over the next seven years until the FD Aircraft has fully captured the market. This means the New Aircraft will command the marketplace until 2008 and then lose increasing share to FD Aircraft until 2015 when their sales will stop. The FD Aircraft will be then be the sole product segment in production aircraft through the end of 2020.

The growth curve of the New and FD Aircraft market segments is estimated from historical production in the 1990s and optimistic targets of 10,000 aircraft in 2013 and 20,000 aircraft in 2020. The data representing the historical points and the target values are shown in Figure 3.3-1.

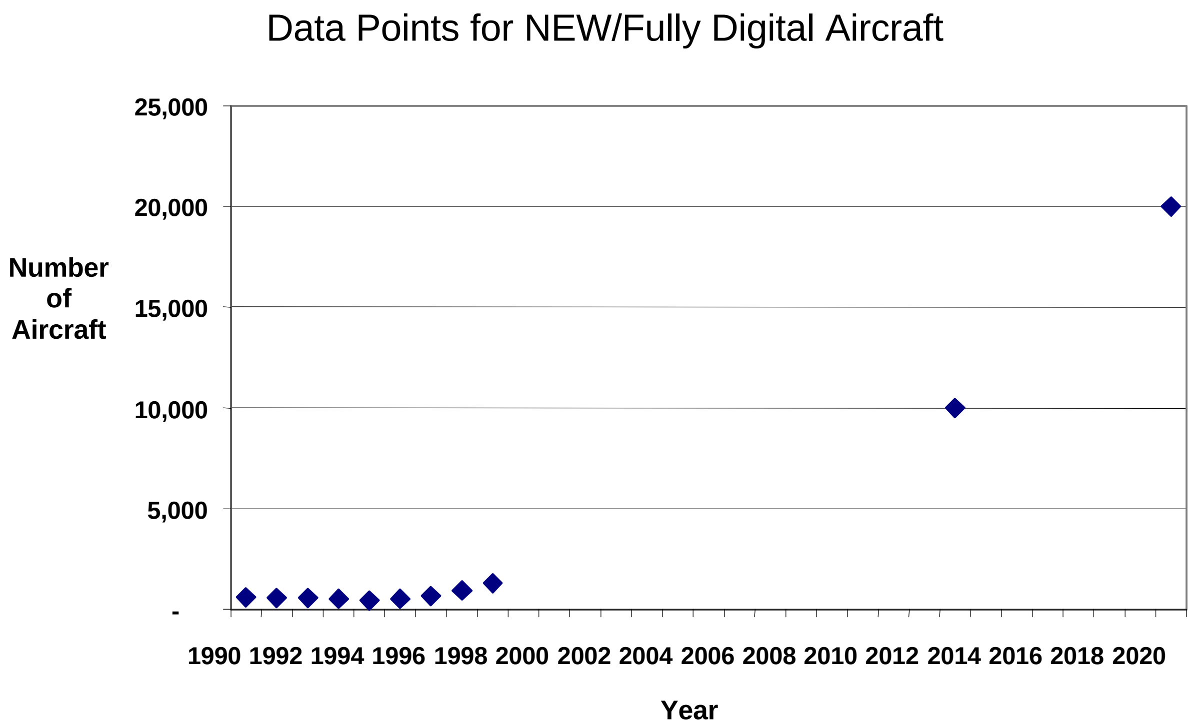

Figure 3.3-1. Data Used to Estimate New/Fully Digital Aircraft Fleet

About 500 - 600 single-engine units were delivered annually in the years 1990 - 1996. This rate increased to 939 aircraft in 1997 and is estimated to exceed 1,300 in 1998 with growth targets estimated for FD Aircraft of 10,000 in 2013 and 20,000 airplanes in 2020. There are many functions that can be used to estimate production in the intermediate years, but the one that best illustrates the intuitive growth of new aircraft during this period is the function:

$$F(x)=a+bx+cx^2+dx^3+ex^4+fx^5+gx^6+hx^7+ix^8$$

where:	a = 34576725294	b = -12769220	c = -25505.69
	d = 9.57534	e = 0.0032292	f = 8.20465
	g = -8.785608	h = -3.258078	i = -3.25807

This equation has an r^2 of 0.99986 for a goodness of fit to the existing points and has an appropriate shape considering the complexities of significantly increasing aircraft production. The graph of this equation through the data points is given in Figure 3.3-2.

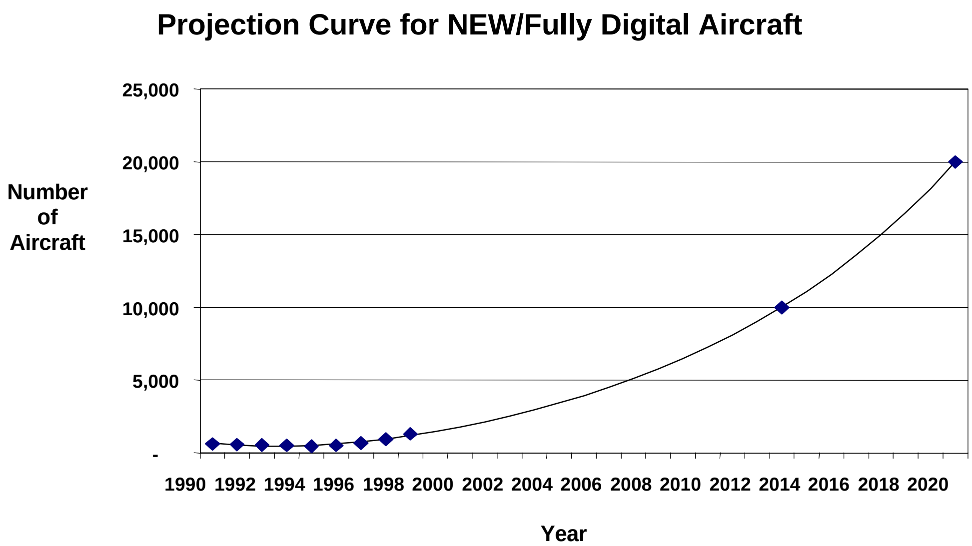

Figure 3.3-2 Projection Curve

The curves in Figure 3.3-3 gives a year-by-year estimate of the total number of New and FD Aircraft produced. In the years, 2008 - 2015, where the New Aircraft production overlaps the FD Aircraft production, the dotted line curve breaks out the number of New Aircraft by year. If one assumes that each FD Aircraft will be equipped with an AHRS but only a portion of the New Aircraft will chose an AHRS, then a reasonable estimate of the percent share of the market is needed for each type of aircraft. This estimate is made by assuming linear growth in market share for the FD Aircraft airplanes in each of the given eight years, resulting in a market share increase of 12.5% per year. Note that this linear increase is not the same as annual growth rate. Rather, it gives the FD Aircraft

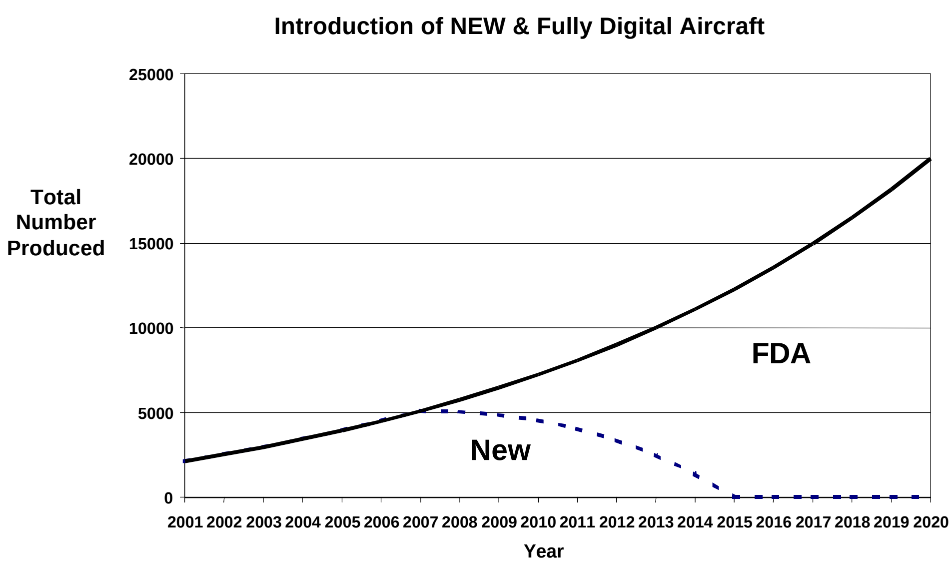

Figure 3.3-3. Introduction of New & Fully Digital Aircraft

12.5% of the market in 2008, 25% of the market in 2009, etc., until 100% of the market share is reached in 2015.

Figure 3.3-4 illustrates the effect of these assumptions on the growth of the single engine piston fleet. It slowly increases to around 170,000 aircraft in 2014 and then sharply increases to 245,000 units as the FD Aircraft reaches full-scale production in 2020.

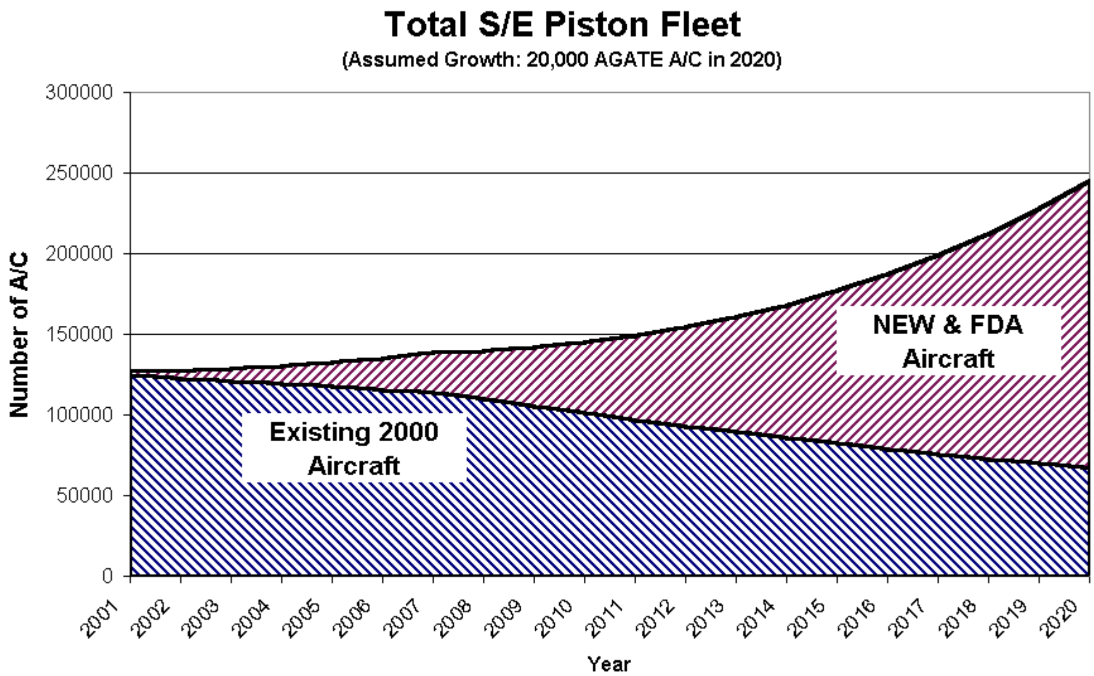

Figure 3.3-4. Total Fleet Over Time

The yearly growth of each segment of the SEP market determines the growth of the total market. Likewise, the AHRS share of each segment of the SEP determines the total AHRS market. The next task is to determine the share of each market segment that will purchase an AHRS each year.

3.4 AHRS Share of the SEP Market Segment

The FD Aircraft market penetration for AHRS will be 100%, because an AHRS is necessary to drive equipment that produces the major benefits of the FD Aircraft. The challenge is to determine the AHRS penetration of the Retrofit Aircraft and New Aircraft markets, where the AHRS is very useful, but not essential.

3.4.1 The Retrofit Aircraft Market

The retrofit market potential for an AHRS includes all aircraft that were not originally equipped with a solid state system that yields magnetic heading and attitude of the aircraft. To be successful in the Retrofit Aircraft market, the AHRS must be upgraded quickly to a primary source of attitude and heading information from an introduction as a secondary stand-alone system. Since single engine piston aircraft comprise the majority of the potential retrofit market, the acceptance of an AHRS by the owners of these aircraft is key to gaining economies-of-scale in its production. Reliably measuring their degree of acceptance is, therefore, key to success of determining the AHRS share of the Retrofit market.

3.4.2 The New Aircraft Market

The precursors of the coming development of New Aircraft market aircraft are available now in the market. This segment of the market will probably embrace the AHRS more readily than the Retrofit Aircraft. This implies that if the Retrofit measure of acceptance were applied to the New Aircraft market, then the estimate of New Aircraft AHRS would be an acceptable, although conservative, number. Thus, the challenge is to determine AHRS acceptance level in the SEP Retrofit Aircraft market.

3.4.3 Price and Demand Curves for the Retrofit Aircraft and New Aircraft Markets

The level of acceptance of a new product by the marketplace depends upon its basic affordability as well as the marketplace perception of the value of the new product. The value of a product to a customer depends upon its perceived functionally verses its cost.

3.4.4 Survey

The perceived functionality of an AHRS versus its price in the SEP retrofit market was measured by a survey given to selected SEP aircraft owners at the 1998 Experimental Aircraft Association's annual air show at Oshkosh, Wisconsin. It was given to a random sample of the aircraft owners who visited the NASA SBIR exhibits building during the show.

Of the 209 surveys completed during the eight days of the show, 196 of them were by SEP aircraft owners. The subjects involved in the survey were shown a 2 by 3 foot copy of the chart contained in Appendix A. This chart was discussed with them and they were explicitly told that they were only getting a secondary source of Pitch, Roll, and Heading. (No autopilot functions or any other feature.) Moreover they were told that it was a complete system including display. The AHRS-based attitude display exhibited 50 feet away by Seagull Technologies, Inc., and the AHRS-based attitude display in the AGATE 1B Beech Bonanza were referenced as representative of the output, with only the three functions provided. After receiving this briefing about the stand-alone AHRS that gives a secondary source of heading, attitude, and 180 of the SEP owners said that if one were available, they would consider buying it for their airplane. They were then asked to name a price range they would be willing to pay for the described functionally. Ninety-six percent of the owners thought that a reasonable price for the described AHRS should be \$5,000 or less. The complete price distribution of the owners is given in Figure 3.4.4-1.

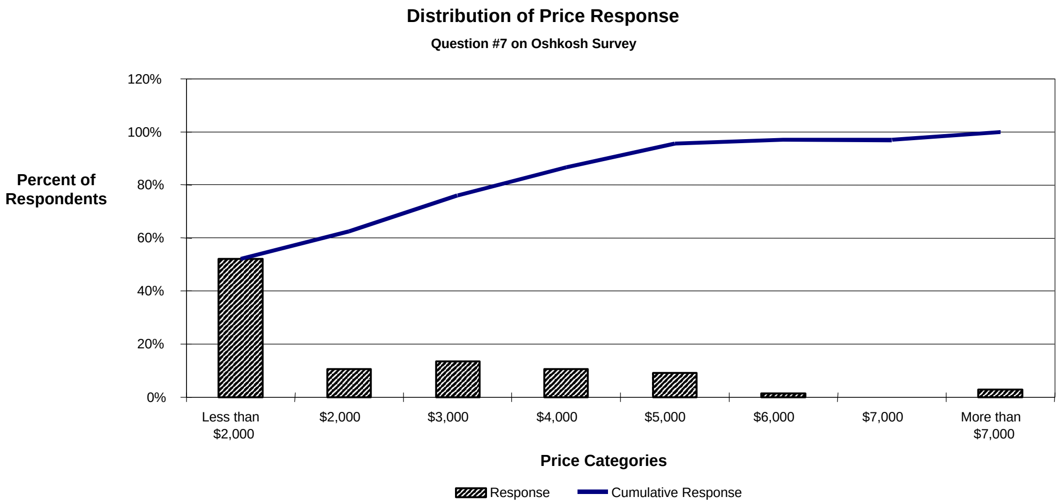

Figure 3.4.4-1. Survey Price Distribution

Once their price was established, the participants were asked to answer the following question: "If an AHRS were available today at the price you stated and you had that amount of money to spend, what would be the percent chance that you would buy the AHRS today?" The participants were given interval choices for their answers so their uncertainty could be measured. The actual two questions from the survey are given below.

7. What would you expect the described AHRS to cost?

1☐ Less than $2,000
2☐ $2,000
3☐ $3,000
4☐ $4,000
5☐ $5,000
6☐ $6,000
7☐ $7,000
8☐ More than $7,000

8. What is the likelihood that you would purchase the described AHRS for the expected cost you gave in question 7?

1☐ Less than 20%
2☐ 20%
3☐ 40%
4☐ 60%
5☐ 80%
6☐ More than 80%

Question 7 asks for the customer's perception of cost for an AHRS. Question 8 asks for the customer's perception of functional utility of an AHRS by asking for the probability that they would purchase one at its expected price. The analysis of these two questions though computer modeling results in the construction of a price-demand curve for the

AHRS in the SEP Retrofit Aircraft market. This curve is also used for measuring demand in the Retrofit Aircraft market, which keeps the Retrofit estimated conservative.

3.4.5 A Simulation Model of AHRS Price-Demand Relationship

Computer simulation is the discipline of designing a model of an actual or theoretical physical system, executing the model on a digital computer, and analyzing the execution output. Simulation replicates the model multiple times and captures the individual results of each replication. The collective results of the simulation are used to answer a certain set or class of questions about the physical system being modeled. A model of the SEP owners response to the survey was built in MicroSoft Excel, then a simulation add-in package, Crystal Ball, was used to add uncertainty and to replicate the model. Crystal Ball, like other modeling tools, extends a spreadsheet's capabilities by including add-in macros that provide new capabilities for probabilistic distributions of inputs, Monte Carlo style inputs, analysis tools and other features. Further, the macros allow multiple runs of a model with probabilistic inputs to collect a meaningfully large data set.

Each SEP owner's AHRS price and probability of purchase was entered in the spreadsheet. A detailed discussion of the spreadsheet and cost model is given in Appendix E. This consisted of 196 rows of data where each row corresponded to an owner's response. For example, if an owner thought the AHRS would cost $3,000 and would purchase it with a probability of 30%, that row would contain a column entry of $3,000 and a column entry of .3. Of course, the owner had a range of acceptable costs and a range of probabilities in mind, but was forced to answer the survey with a discrete value. That value may be thought of as the most likely value for the answer to the question. The true uncertainty of the owner's answer is inserted into the model by the use of an interval estimate. The interval has the owners answer as the most likely value then estimates a pessimistic and an optimistic value. The three values are then use to form a triangular probability distribution.

The triangular distribution shows the variability when the minimum, maximum, and most likely values are known. The parameters for the triangular distribution are Minimum, Maximum, and Most Likely.   There are three conditions underlying triangular distribution:

1) The minimum number of items is fixed.
2) The maximum number of items is fixed.
3) The most likely number of items falls between the minimum and maximum values, forming a triangular shaped distribution, which shows that values near the minimum and maximum are less apt to occur than those near the most likely value.

If an owner's estimate of the cost of an AHRS was c, then the minimum cost was fixed at c-$1000 and the maximum cost was fixed at c+$1000. Likewise, given that the most likely probability, p, of purchase was given by the owner, the minimum value of the probability was fixed at p-.1 and the maximum value of the probability was fixed at p+.1.[26] These values were used to define triangular distributions for each owner's response to the cost and likelihood of purchase questions. Each triangular distribution was entered into the model by using Crystal Ball.

Considering only the two triangular distributions of the owner's response to survey questions 7 and 8, one replication of the model will generate a cost between c-1000 and c+1000 and a probability of purchase between p-.1 and p+.1. The triangular distributions, by definition, will be more likely to generate numbers close to c and p rather than close to the boundary points of the distribution.

Two additional distributions were entered into cells on the owner's row. The first was a uniform probability distribution with a minimum of 0 and a maximum of 1. In a uniform distribution, all values between the minimum and maximum are equally likely to occur. The parameters for the uniform distribution are Minimum and Maximum and there are three conditions underlying a uniform distribution:

1) The minimum value is fixed.
2) The maximum value is fixed.
3) All values between the minimum and maximum are equally likely to occur.

The second is also a uniform distribution, this time with a minimum of 3000 and a maximum of 9000, is inserted in a cell in the spreadsheet model. This distribution is used to generate a random price for an AHRS between $3,000 and $9,000 with each replication of the model.

Given the triangular distribution of the above owner's answers to Questions 7 and 8, the uniform distribution between 0 and 1 for the owner, and the uniform distribution between $3,000 and $9,000 for the price, a replication of the model will generate four numbers. It will generate a price for the AHRS, a price the owner would pay, a probability of purchase for the owner, and a randomly selected number between 0 and 1 for the owner (according to the owners uniform distribution.) Suppose the uniformly generated price for the model is $2,976, the triangular generated price for the owner is $3,334, the probability of purchase for the owner is .2788, and the uniformly generated number between 0 and 1 for the owner is .1569. Then since the owner price is greater than the model price and the owner probability of purchase is greater than the owner uniformly generated number between 0 and 1, the owner in this replication purchased the AHRS. Results from additional replications of the model are given in Table 3.4.5-1.

[26] Note that this choice of minimum and maximum value "fills in the gaps" in the response options for Questions 7 and 8 on the survey.

Table 3.4.5-1. Examples of Replications

Replication	Owner Price	Owner Probability	Owner Uniform Probability	Model Price	Result: Purchase
2	$4,443	0.3489	0.5234	$3,567	No
3	$6,867	0.2978	0.1157	$7,498	No
4	$3,205	0.3798	0.3325	$3,156	Yes
5	$5,956	0.2256	0.1566	$3,067	Yes

For each replication, or event, a price is established for the AHRS and a determination is made whether each owner bought the AHRS in that replication. The purchase depends upon two events. First, the owner price must be greater than the model generated price and second, the owner uniformly generated probability must be less than the owner triangular generated probability. The owner uniform probability serves as a coin toss to determine if the owner indeed purchases the AHRS. For example, if the owner probability of a purchase is .3, then the owner will purchase the AHRS 30% of the time. This is inserted in the model by having the owner purchase the AHRS if the uniformly generated probability is a number less than .3.

Since for a given model generated price, it can be determined if each owner purchased the AHRS at that price, the probability of an owner purchasing the AHRS for one replication can be determined by the ratio of those who purchased to 196, the total number of owners. Since the owners purchase is dependent upon the value of the uniformly generated probability relative to the triangular probability, the same model generated price may yield a different number of owners who purchase. However, by replicating the model many times, the probability function can be determined. This is similar to trying to determine the probability of one head and two tails (H,T,T) in the toss of three coins. If we toss the coins five times, we may get the desired outcome only once. The ratio of favorable outcomes to total outcomes is 1/5, but we know that if we replicated the coin toss many times the ratio will converge to the true probability of 3/8.

To build a price-demand curve for the AHRS, the interval ($9,000, $3,000) is subdivided into $100 increments and the model is replicated 5,000 times. For each model generated price, the number of owners who purchased are counted and then added to the number accumulating for the given $100 price interval; and the total number of owners for that interval is increased by 196. For example, suppose for a model generated price of $4,358, and there are 87 owners who purchase at that price. In the price interval of ($4,300, $4,400), 87 is added in the successes cell and 196 is added in the total owners cell. Now suppose that the next time the model generates a price in this interval, say $4,396, there are 118 owners who purchase. The number in the successes cell is increased by 118 and the number in the total cell is increased by 196. As more and more model-generated prices hit the designated cell, the ratio of the successes to the total converges to the probability of an owner purchase of an AHRS priced between $4,300 and $4,400.

Figure 3.4.5-1 shows the probability generated by the model for each $100 bin in the price interval from $9,000 to $3,000. The upper bound of $9,000 was chosen for the price interval because prices greater than $9,000 generate a probability of purchase very near zero. The probability of an AHRS purchase by a single engine piston aircraft owner increases as the price of the AHRS fall below $9,000 but a reasonable lower bound of $3,000 was chosen for the price interval. There are two distinct plateaus in the probability distribution. The first is from $9,000 to $8,400 where the probability of an AHRS purchase is extremely low. The second plateau is from $7,400 to $6,000. The probability of the purchase of an AHRS steadily increases outside of these two plateaus.

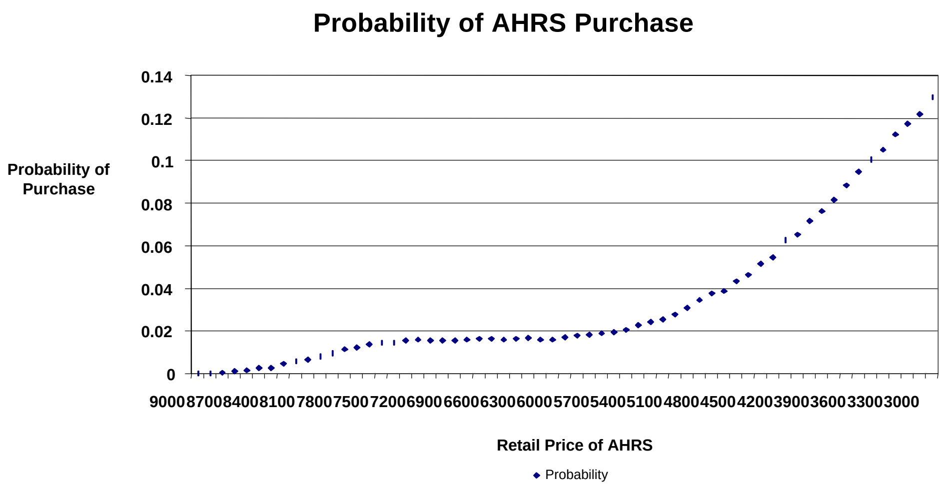

Figure 3.4.5-1. Probability of AHRS Purchase

The demand function, representing the probability of an AHRS purchase for a given price, is an exponential function that continually increases through the given points. Figure 3.4.5-2 reveals the function and its fit to the probability data generated by the model. Note that a price of $9,000 in 2001 will yield about 10 expected sales in the projected retrofit market. This implies that to tap the SEP retrofit market, the AHRS price can not exceed $9,000 initially and it must decrease rather sharply over time to gain market share.

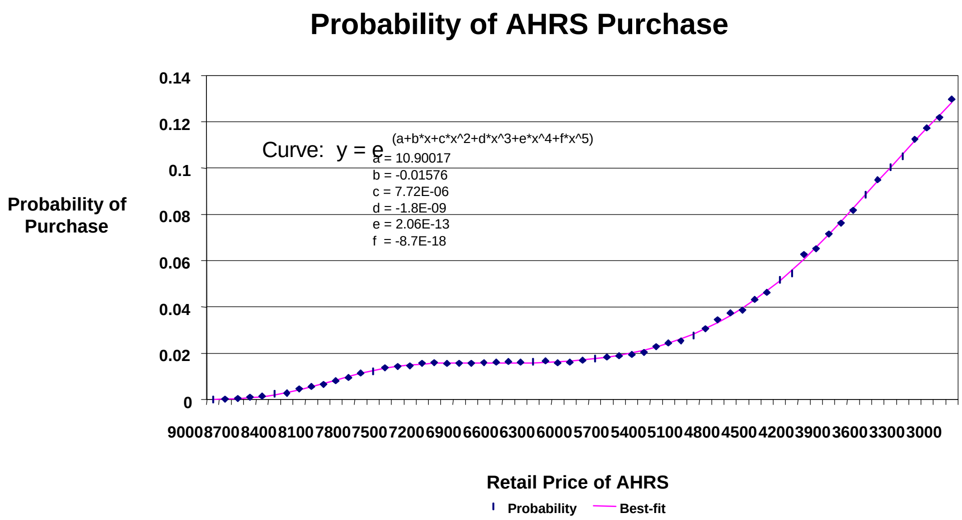

Figure 3.4.5-2. Probability of AHRS Purchase Function

3.4.6 Verifying the Price Decay Curve Over Time for an AHRS

The price of solid state avionics equipment decreases over time due to advances in manufacturing technology and achieving economies-of-scale as a result of increased acceptance of the product by the marketplace. After reviewing FAA historical data on avionics installations, it was found that this is best illustrated by considering the introduction of RNAV systems.

RNAV system cost data was reviewed for the years 1970, 1984, and 1990. The data were normalized to 1998 dollars to compare cost decline across multiple years. The normalized cost data are given in Table 3.4.6-1.

In the earliest days, NARCO's RNAV system prices initially were over $12,000 and then fell to about $5,000 by 1990. It is difficult to draw detailed trends from the numbers in Table 3.4.6-1. For example, from 1984 to 1990, the lowest cost units went up from about $3,000 to $5,000 in constant dollars. Meanwhile, the King KNS 80 went from $9,620 to $10,296, the King KNS 81 went from $9,738 to $7,893, and the Foster 612 went from $10,846 to $8,658. Nevertheless, the prices overall are clearly trending downwards.

The King KNS 81 and the Foster 612 decreased in price and, being the same model number with the same general features, are probably the best examples of common RNAV system purchases through recent years for single engine airplanes. Their lower price indicates that their target market was probably general aviation and they were both introduced later as the RNAV system technology matured.

Since there are large differences in the features that these units provide (the highest cost items were sold for airliners and heavy corporate jets), aggregating all of these units

Table 3.4.6-1. RNAV Price Decline

HISTORICAL RNAV PRICING			
YEAR	MFR.	MODEL	PRICE in 1998$
1970	NARCO	CLC-60	$12,246
1970	BUTLER	VAC	$66,628
1984	FOSTER	511	$2,986
1984	NARCO	860	$3,136
1984	ARC	RN-478A	$5,580
1984	ARC	RN-479A	$5,659
1984	COLLINS	ANS-351	$6,091
1984	BENDIX	NCP-2040	$7,050
1984	KING	KNS 80	$9,620
1984	KING	KNS 81	$9,738
1984	FOSTER	612	$10,846
1984	ARC	RN-1079A	$10,924
1984	KING	KNR 665A	$26,957
1984	COLLINS	ANS-31C	$28,435
1984	COLLINS	ANS-31A	$31,382
1984	COLLINS	NCS-31A	$48,476
		Average	$14,777
1990	NARCO	NS-801	$5,013
1990	FOSTER	612/A	$5,709
1990	NARCO	NS-800	$6,452
1990	KING	KNS 81	$7,893
1990	FOSTER	612	$8,658
1990	COLLINS	ANS-351	$9,323
1990	KING	KNS 80	$10,296
1990	FOSTER	601B	$11,293
1990	KING	KNS 81-30	$13,069
		Average	$8,634

would not represent general aviation acceptance of RNAV system, but it would give a broader base to view the price decay over time.

Table 3.4.6-2 calculates the decay curve associated with the Foster 612, the King KNS81, as well as the average price for all RNAV systems from 1984 to 1990. Note that Year 1 corresponds to 1984 and, consequently, Year 6 shows the 1990 values for each column. The percent of initial cost remaining in Year 20 is 34%, 70%, and 41%, respectively.

The initial price of the AHRS in 2000, excluding certification costs, is estimated to be $9,000 by comparing the prices of non-certified, solid state AHRS currently on the market. Using the three decay curves represented by each column in Table 3.4.6-2 to estimate the price of an AHRS in 2020, one gets $3,077, $6,334, and $3,664, respectively. Assuming that the technology impact on price continues to strengthen, a price of $3,000 for an AHRS in 2020 would not seem unreasonable as an optimistic value. Again using Table 3.4.5-2 to estimate an upper bound for an AHRS in 2020, $7,000 appears to be a reasonable pessimistic value since it exceeds the largest price estimate from Table 3.4.6-2. To complete the triangular distribution of the AHRS price, the most likely value in 2020 is chosen to be $5,000.

The price decay curves from $9,000 to $3,000, $5,000 and $7,000 in the time frame of 2000 to 2020 is best represented by an exponential decay curves since we know that technology advances in solid state electronics is exponential. Fitting exponential decay curves to these values yield the functions given in Figure 3.4.6-1. (The certification cost required for installation in a non-experimental aircraft is excluded from the determination of these price curves, and is included later in the analysis.)

Table 3.4.6-2. Historical Price Decay

Year	FOSTER Model 612	KING Model KNS 81	Average
1	10846	9738	14777
2	8462	8978	12003
3	7318	8561	10629
4	6601	8277	9750
5	6094	8063	9119
6	5709	7893	8634
7	5402	7751	8244
8	5150	7631	7920
9	4937	7526	7645
10	4754	7434	7408
11	4595	7351	7199
12	4454	7277	7014
13	4328	7209	6847
14	4215	7146	6697
15	4112	7089	6560
16	4018	7035	6434
17	3932	6986	6318
18	3852	6939	6210
19	3778	6895	6111
20	3709	6854	6017

3.5 AHRS Sales by Year Simulation

The development of an estimate for AHRS sales in the Retrofit, New, and FD Aircraft markets consists of modeling the sales in each segment by year. It is assumed that FD Aircraft airplane will incorporate AHRS for its flight control system. It is further assumed that Retrofit and New Aircraft will adopt the technology in accordance with the price-demand curve given in Figure 3.4.5-2.

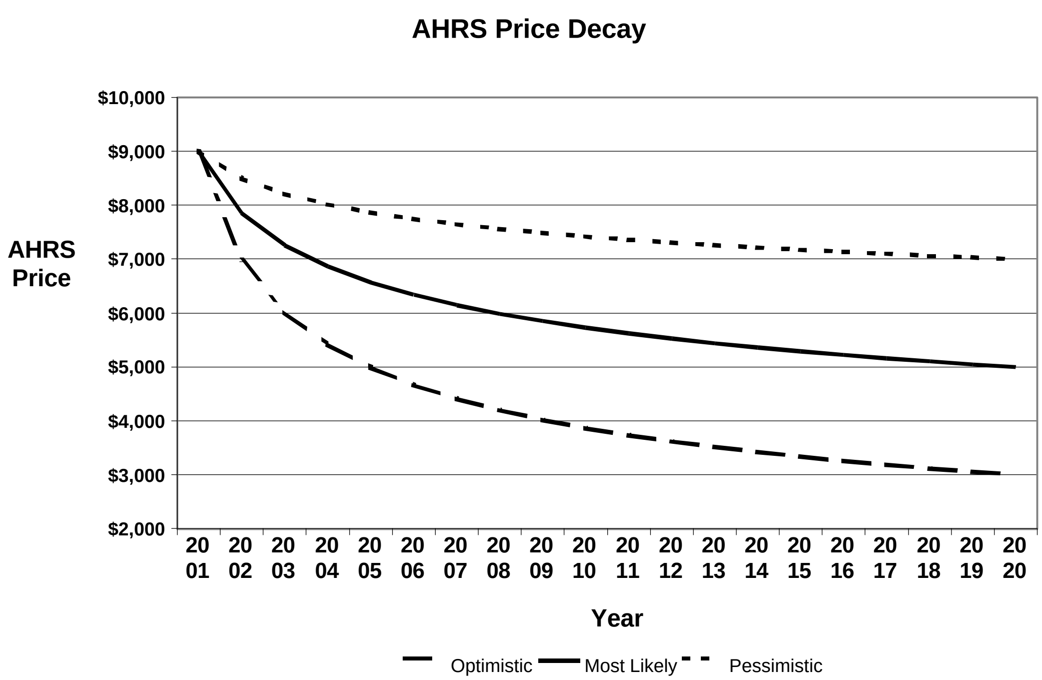

Figure 3.4.6-1. AHRS Price Decay

3.5.1 Introducing Uncertainty into the Model

The uncertainty in the number of aircraft in the New Aircraft market per year is optimistically estimated by the top curve in Figure 3.5.1-1 which is the New Aircraft market portion of the curve displayed in Figure 3.3-2. The Most Likely and Pessimistic curve are 90% and 80%, respectively, of the Optimistic curve. The curves are then used to build a triangular distribution for the New Aircraft AHRS sales model for New Aircraft market. A value from this distribution is chosen for each of these years for each replication of the sales model and stored in the model's memory. Replicating the sales model adds the desired uncertainty of the New Aircraft market sales forecast into the results of the model.

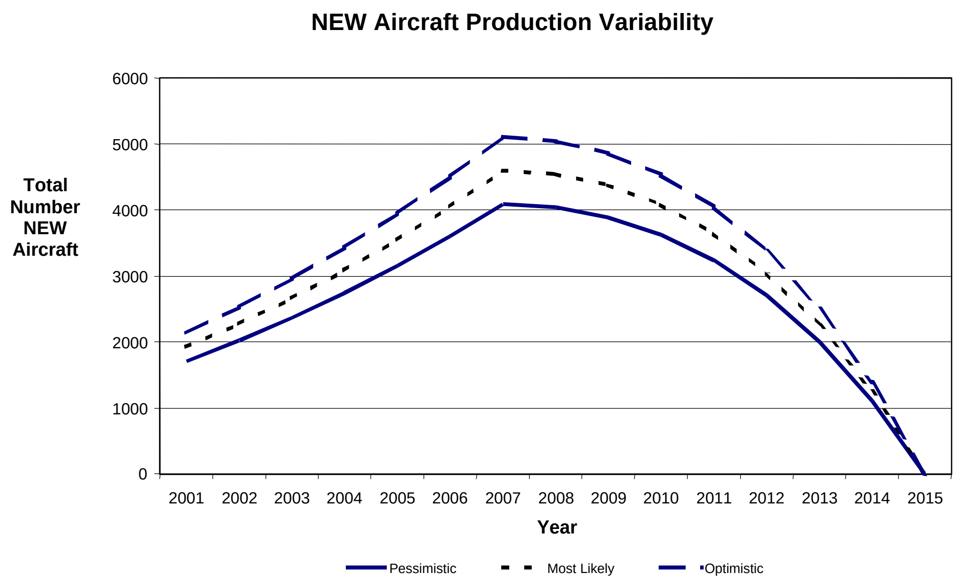

Figure 3.5.1-1. Uncertainty of New Sales

The number of FD Aircraft produced is optimistically estimated by the top curve in Figure 3.5.1-2, the most likely number of FD Aircraft is estimated by the middle curve and the pessimistic number of FD Aircraft produced is estimated by the lower curve. This gives an optimistic value of 20,000, the most likely estimate of 10,000 and the pessimistic value of 3,000 aircraft in 2020. These values are used in a triangular distribution for FD Aircraft sales to accommodate the uncertainty of the sales in 2020.

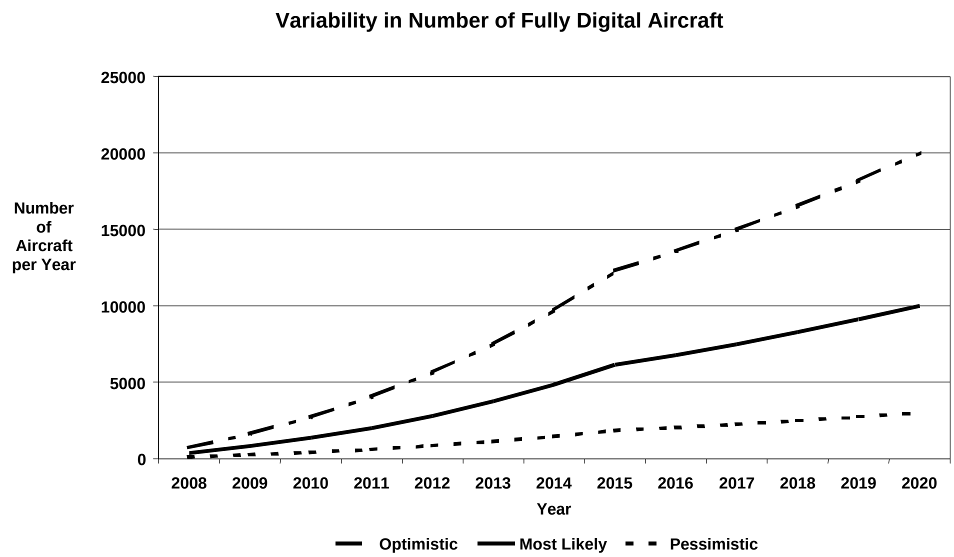

Figure 3.5.1-2. Uncertainty of Fully Digital Aircraft Sales

3.5.2 Completing the AHRS Sales Model

Now that the degree of uncertainty of the estimates has been entered into the AHRS sales model, the rest of the model can be built. The goal of the model is to estimate an expected yearly revenue for AHRS manufacturers. The yearly AHRS price and the AHRS sales volume by year from the base year of 2000 until the year 2020 must be calculated to determine yearly revenue. Once revenue by year has been determined, the cumulative AHRS revenue by year may also be calculated.

To calculate the number of AHRS sold in year Y for one replication of the model, a price for the AHRS in year Y is first determined. The price, P, for year Y is calculated by a triangular distribution driven by the optimistic, most likely, and pessimistic values shown in Figure 3.4.6-1. The calculated price, P, then determines via the price -demand curve, the probability p, of an AHRS purchase at P in the Retrofit Aircraft and New Aircraft markets. The number of aircraft eligible for basic AHRS in the Retrofit Aircraft market, R, is calculated by subtracting the Y-1 years of attrition and then the aircraft who purchased an AHRS in previous years from the estimated size of the 1999 fleet. The number of New Aircraft, N, in year Y is then calculated by using its respective share of the market in year Y as illustrated by Figure 3.3-3 and the uncertainty of the New Aircraft estimates as illustrated in Figure 3.5.1-1. The number of FD Aircraft, A, in year Y is calculated from the FD Aircraft share of the market in year Y and the uncertainty of the FD Aircraft estimate in year Y as illustrated by Figure 3.5.1-2. It is assumed that an AHRS is included in each FD Aircraft. The estimated number of AHRS sold in year Y, AHRS(Y,P), is calculated as AHRS(Y,P) = p(P)*(R+N) + A. Table 3.5.2. shows the calculations for the first five years through four replications.

Each replication of the AHRS sales model calculates the AHRS(Y,P) for each of the years from 2000 through 2020 and the values are stored in results of the model. The

Table 3.5.2. Calculating Cumulative Sales Volume

Replication	Year	Simulated Purchase Price of AHRS	Probability of Retro Purchase	Number of Retro A/C who Purchase	Number of SE Aircraft Left w/o AHRS	Attrition on the Current (1996) Fleet	Total Number of AHRS Sold to the Fleet	Number of New Aircraft Simulated	Number of New A/C and FD A/C who Purchase	Number of Retrofit, New A/C and FD A/C who Purchase Each Year	Cumulative Retrofit, New, & FD A/C who Purchas
	2001	9000	0.00009	10	124927	124927	10	800	0	10	10
	2002	8197	0.00552	678	123023	123033	688	939	5	683	693
1	2003	6491	0.01579	1903	120505	121193	2591	1118	18	1921	2614
	2004	6267	0.01610	1881	116816	119407	4472	1360	22	1903	4517
	2005	6416	0.01586	1795	113201	117673	6267	1629	26	1821	6338
	2001	9000	0.00009	10	124927	124927	10	806	0	10	10
	2002	8209	0.00534	656	123023	123033	666	943	5	661	671
2	2003	7510	0.01429	1721	120527	121193	2387	1143	16	1737	2408
	2004	6230	0.01619	1895	117020	119407	4282	1382	22	1917	4326
	2005	6767	0.01579	1790	113391	117673	6072	1662	26	1816	6142
	2001	9000	0.00009	10	124927	124927	10	793	0	10	10
	2002	7798	0.01135	1396	123023	123033	1406	957	11	1407	1417
3	2003	7447	0.01470	1760	119787	121193	3166	1145	17	1777	3194
	2004	5993	0.01710	1987	116241	119407	5153	1381	24	2011	5204
	2005	5805	0.01830	2058	112520	117673	7211	1641	30	2088	7292
	2001	9000	0.00009	10	124927	124927	10	817	0	10	10
	2002	8156	0.00611	752	123023	123033	762	941	6	758	768
4	2003	7448	0.01469	1769	120431	121193	2531	1122	16	1785	2553
	2004	6827	0.01581	1847	116876	119407	4378	1346	21	1868	4422
	2005	7818	0.01110	1257	113295	117673	5635	1612	18	1275	5696

cumulative AHRS sales for year Y is then calculated by $\Sigma(Y) = AHRS(Y,P) + \Sigma(Y-1)$. Table 3.5.2 shows the cumulative AHRS sales total in the last column.

Note that in the data collected in Table 3.5.2 there are no FD Aircraft. This is because the production of FD Aircraft does not start in the model until 2008. Similar views of the model data in the years beyond 2007 would show the gradual build-up of FD Aircraft.

Each replication of the AHRS sales model generates a large collection of data that is stored in the model results. A simulation consists of enough replications of the model to assure that the sample data are sufficient to yield statistically significant conclusions. The number of replications used in the AHRS sales model was 5,000. This means that 5,000 values from the price interval for each year were chosen to drive the year-by-year and cumulative sales results. The 5,000 year-by-year and cumulative sales values generated were captured by the model and are displayed by means of a trend chart. Trend charts display the results of the AHRS sales model over time measured in years. But even more information can be derived from the trend data as described in the next section.

3.5.3 Displaying the AHRS Sales Model Results

A trend chart is displayed as a series of layered certainty bands, each one representing a particular certainty level. A 25% certainty band, for instance, means that 25% of the simulated values for the selected forecasts lie within the band. This otherwise is equivalent to choosing a 25% certainty level for each forecast, then displaying the certainty ranges side-by-side in a connecting ribbon. The minimum and maximum end-points of the certainty ranges are on the value axis to the left of the chart area.

The certainty bands chosen for the AHRS sales model trend charts are the 10%, 25%, and 50% certainty levels. The trend chart presented in Figure 3.5.3-1 shows AHRS sales by year. The chart reveals that the sale volume of AHRS remains steady until the introduction of the FD Aircraft airplane in 2008. It then sharply increases throughout the remaining time frame.

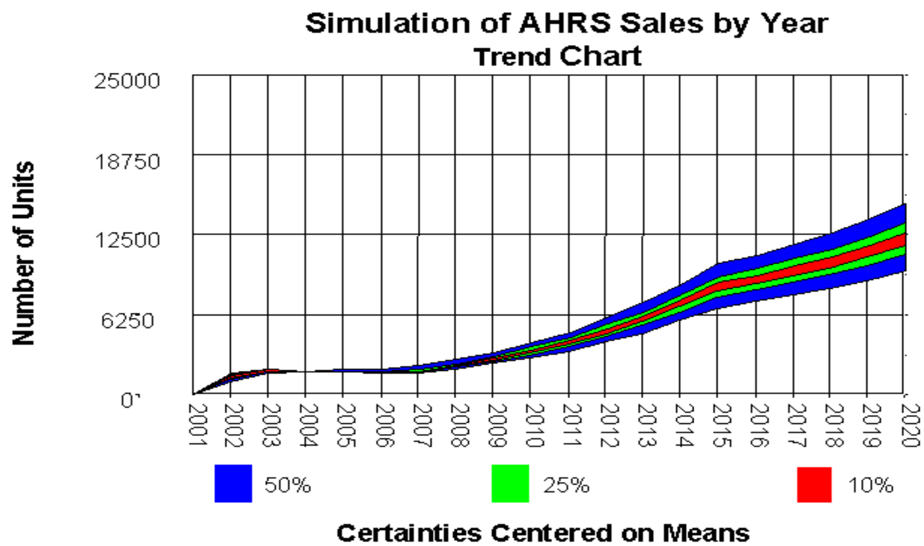

Figure 3.5.3-1. AHRS Sales by Year

The yearly results captured by the model give a clearer view of the sales activity for a particular year. The forecast statistics for the year 2020 is given in Table 3.5.3-1.

Table 3.5.3-1. AHRS Sales Forecast Statistics for Year: 2020

Forecast: AHRS Sales in 2020	
Statistic	Value
Trials	5,000
Mean	12447
Median	12196
Standard Deviation	3620
Range Minimum	3832
Range Maximum	22947
Range Width	19115

Note how the uncertainty in the estimates of the AHRS price and aircraft volume yield uncertainty in the number of projected AHRS sold. However the uncertainty is quantified with a minimum value of 3,832 units and a maximum value of 22,947[27] units sold in 2020. The expected number of units sold in 2020 is 12,447.

The AHRS sales model also saves the cumulative sales data by year and presents it in either a trend chart, Figure 3.5.3-2, or as a table of descriptive statistics, Table 3.5.3-2.

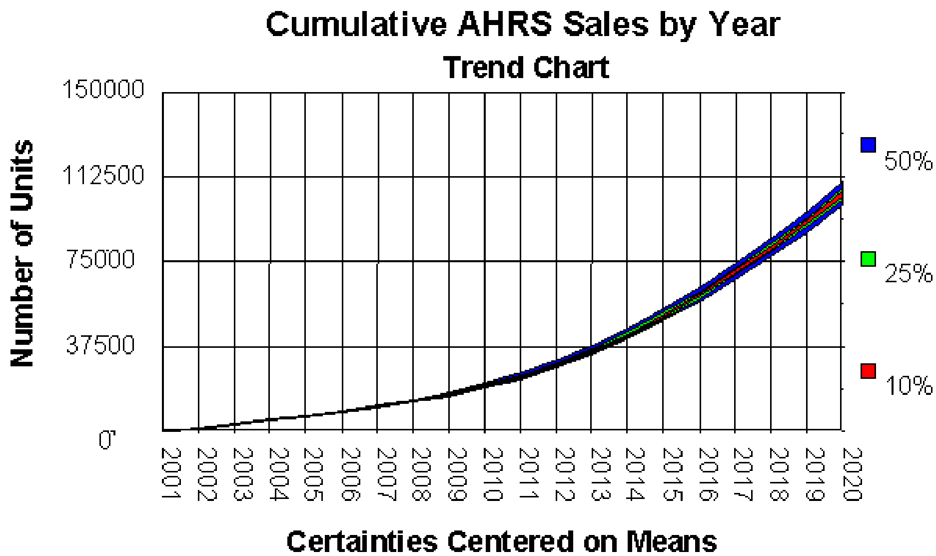

Figure 3.5.3-2. AHRS Cumulative

Table 3.5.3-2. Cumulative Sales Statistics for Year 2020

Forecast: Cumulative Sales for 2020	
Statistic	**Value**
Trials	5,000
Mean	105802
Median	105851
Range Minimum	80003
Range Maximum	137030
Range Width	57027

Note that the cumulative AHRS sales exceed 80,000 units by the year 2020. The uncertainty in the initial estimates is again reflected in the uncertainty of the results. Note that the cumulative sales volume estimate of the AHRS ranges from a low of 80,003 to a high of 137,030. The expected cumulative number of AHRS sales is 105,802 units.

[27] In one iteration of the simulation in the year 2020 there were 22,947 AHRS sold to both the FD Aircraft market and the Retrofit market. Since no more than 20,000 can be sold in the FD Aircraft market in 2020, the Retrofit market for this one iteration exceeded 2,947.

3.6 Volume Required For Profitability

To conclude the analysis, an estimate is developed of the minimum market for a low-cost AHRS required to support sufficient interest in the manufacturing industry to produce such a product. Two scenarios are developed: 1) a minimum number of aircraft incorporating a low-cost AHRS each year that will generate a 20% net profit, and 2) an estimated net profit determined by the price and volume assumptions presented in this paper.

A baseline minimum number of AHRS produced for New Aircraft and FD Aircraft markets needed to return a net profit of 20% over the twenty-year period is determined by estimating[6]:

Profit level of 25% without considering R&D and Certification costs
R&D costs for the basic AHRS to be $1,000,000
Certification cost for the basic AHRS to be $1,000,000
R&D costs to increase functionality to FD Aircraft AHRS to be $500,000
Certification cost for the FD Aircraft AHRS to be $1,000,000.

Based upon these assumptions the growth curve of New and FD Aircraft must climb to 3,000 units per year in 2020 as illustrated in Figure 3.6-1.

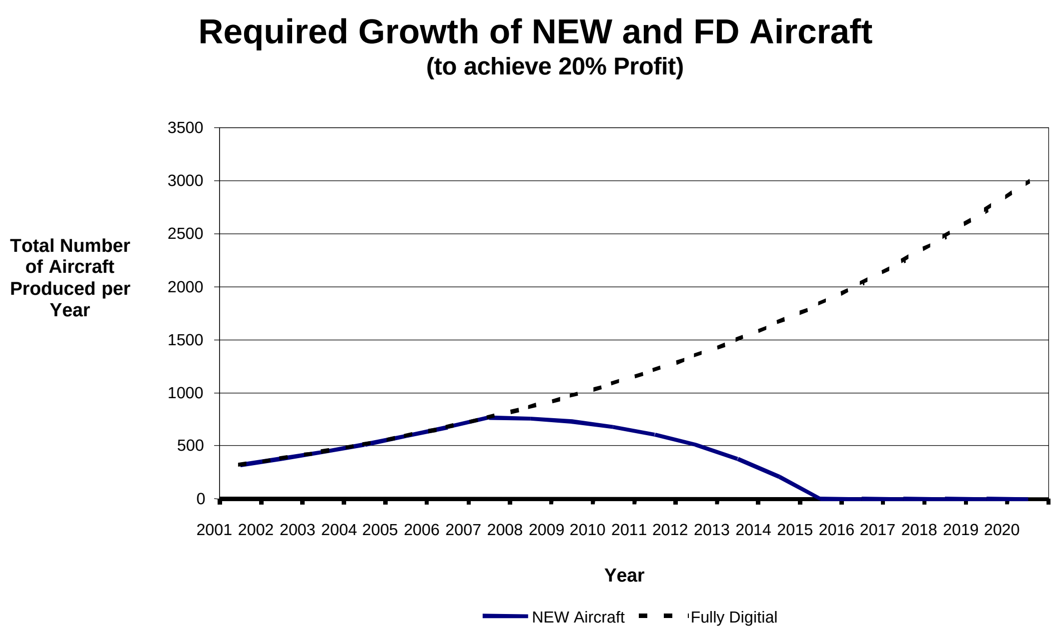

Figure 3.6-1. Baseline Growth

Given the current activity to revitalize the general aviation industry, the growth of new production aircraft as displayed in Figure 3.3-2 should easily be achieved. This encouraging result is enhanced by a break-even point of three years and a positive profit through the investment in the FD Aircraft AHRS as shown in Figure 3.6-2.

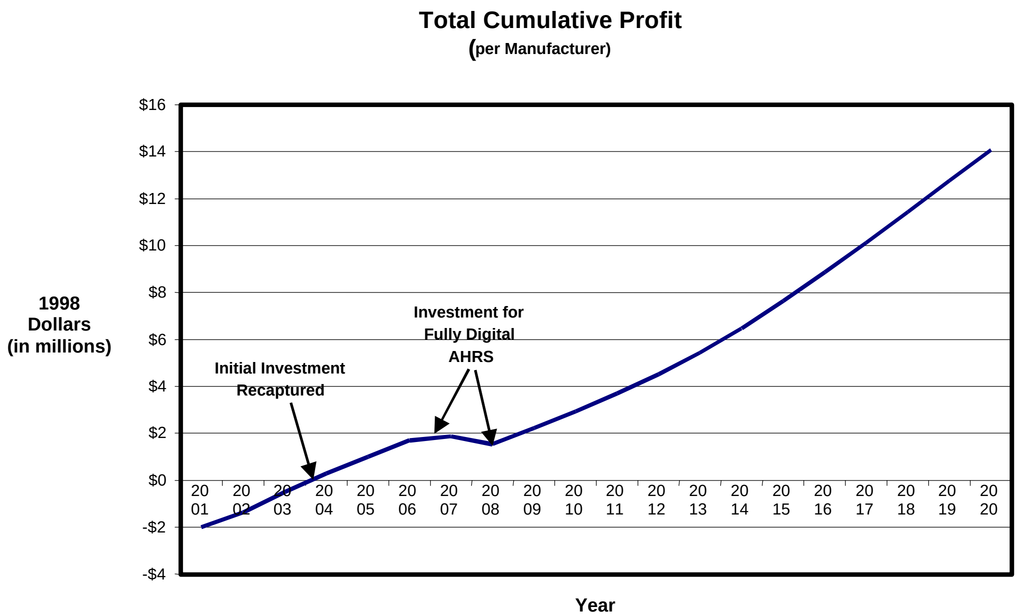

Figure 3.6-2. Profit Picture

The next step in the analysis is to estimate a reasonable profit based upon production targets set over the period of 2001 to 2020. This in turn yields a reasonable return expected from the introduction of a basic AHRS and its refinements through to the FD Aircraft AHRS.

Estimating a reasonable growth curve for general aviation production aircraft involves uncertainty as does estimating a future price decay curve. A mathematical model is built to capture this uncertainty and incorporate it into the profit forecast.

To capture the uncertainty in the price decay curve, three curves are used to define a triangular distribution for the price. The triangular distribution is based upon optimistic, most likely, and pessimistic estimates. All three curves start at $9,000 in 2001, but the optimistic price decay curve drops to $3,000 in 2020, the most likely price decay curve drops to $5,000 in 2020, and the pessimistic price decay curve drops to $7,000 in 2020. Likewise a triangular distribution is established for the production growth curves by choosing 3,000 units in 2020 as a minimum value, 10,000 units in 2020 as the most likely value, and 20,000 units in 2020 as an optimistic value.

Five thousand iterations of the mathematical model representing this uncertainty gave the following results about the net profit:

➔ The forecasted profit over the 20-year period ranged from 21.54% to 23.06%

➔ The expected profit was 22.50%

Table 3.6-1 and Figure 3.6-3 below summarize the results of the simulation model showing the probable profit over the 20-year period.

Table 3.6-1. Forecast Profit over the 20-Year Period

Forecast: Profit	
Statistic	**Value**
Trials	5,000
Mean	22.50%
Median	22.50%
Standard Deviation	0.18%
Range Minimum	21.54%
Range Maximum	23.06%

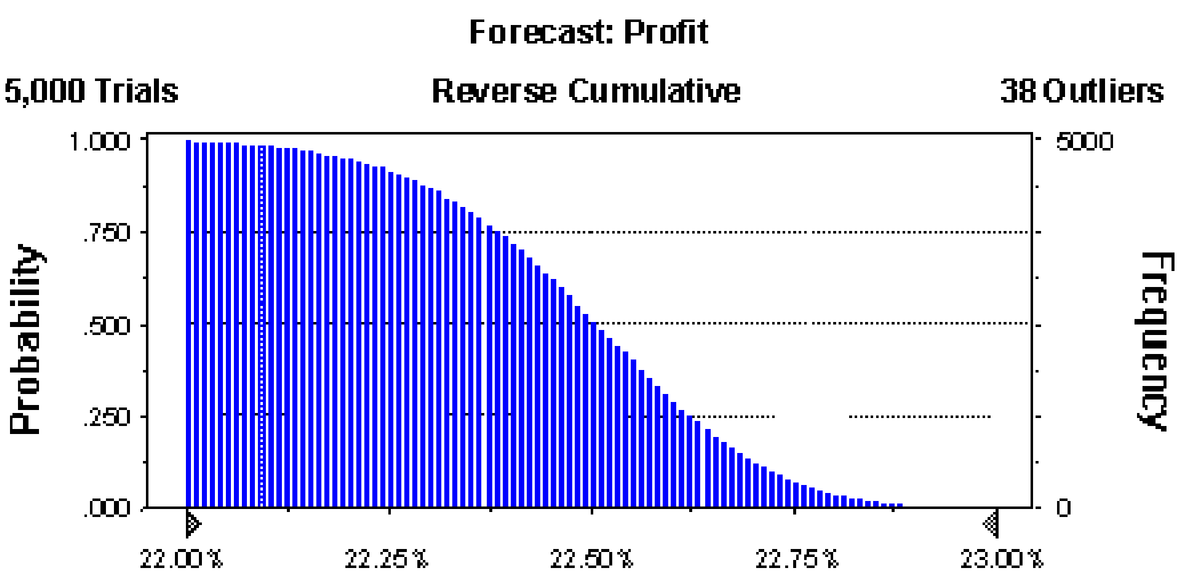

Figure 3.6-3. Probable Profit over the 20-Year Period

3.7 Assumptions Used In Analysis

A list is provided in Table 3.7-1 below of the assumptions used in this analysis.

Table 3.7-1. Assumptions

Assumption Item	Year	Value
1. Optimistic number of FD aircraft	2020	20,000
2. Most Likely number of FD aircraft	2020	10,000
3. Pessimistic number of FD aircraft	2020	3,000
5. Price of basic AHRS in the Retrofit Market (Excluding Certification Costs)	2001	$9,000
6. Optimistic Price of AHRS	2020	$3,000
7. Most Likely price of AHRS	2020	$5,000
8. Pessimistic price of AHRS	2020	$7,000
9. Cost of basic AHRS (Retrofit market) certification	2000	$1,000,000
10. Cost of R&D for basic AHRS (Retrofit market) certification	2000	$1,000,000
13. Cost of FD Aircraft AHRS (Future market)certification	2008	$1,000,000
14. Cost of R&D for FD Aircraft AHRS (Future market) certification	2008	$500,000
15. Start of New market Aircraft Production	2001	
16. End of New market Aircraft Production	2015	
17. Start of FD Aircraft (Future market) Production	2008	
18. Number of AHRS manufacturers	2000	4
19. Percent of Market FD Aircraft (Future market) captures from New market each year		12.5%
20. Variation in the New Aircraft market aircraft production		20%
22. Single Engine Piston fleet attrition until 2007		2.1%
23. Single Engine Piston fleet attrition after 2007		4.0%

4. AHRS Production Assessment

Substantial effort remains after completion of a working prototype before production units are available for sale in the marketplace. Consequently, much of the risk that remains in bringing a low-cost AHRS successfully to market involves the risks associated with production. This assessment of production risk is intended to encompass everything required for the manufacture, distribution, marketing, and support of the AHRS product.

Table 4-1 summarizes the level of risk associated with the major elements of producing the solid state AHRS designs. The risk is given for three company categories where:

1. a new manufacturer is one that does not yet have a production facility for TSO’d equipment intended for certified aircraft;
2. a small manufacturer produces a moderate amount of TSO’d avionics for light aircraft; and
3. a large manufacturer is one that has extensive production facilities for building a wide range of TSO’d avionics for many types of aircraft.

Table 4-1. AHRS Production Risk

Risk Element	New Manufacturer	Small Manufacturer	Large Manufacturer
Capital Requirements	High	Med	Low
Production Preparations	High	High	Med
Production Tooling and Setup	Med	Low	Low
Establishing a Quality System	High	Med	Low
Manufacturing Operations	High	Med	Low
Marketing	Med	Low	Low
Product Support	High	Med	Low
Other Functions	Low	Low	Low

Risks are generally much higher for a company that must build its entire AHRS production capability from the ground up, and generally lower for a company that already possesses the equipment, processes, and skills to produce the AHRS. Since the risks associated with creating a production capability can be managed in many ways, two widely different approaches are reviewed below to indicate the range of considerations affecting these risks.

The first approach looks at the production start-up tasks facing an AHRS developer that does not yet have any production capability, while the second approach involves licensing arrangements with an established avionics manufacturer.

4.1 Production Start-up by Developer

It is assumed in this analysis that the AHRS developer is primarily an R & D company with a prototype shop. In this case, a production startup involves acquiring assets and developing capabilities in five main categories:

1. capital requirements and acquisition,
2. production preparations,
3. manufacturing,
4. marketing, and
5. product support.

4.1.1 Capital Requirements and Acquisition

The production facilities and associated land comprise the greatest portion of capital costs. In addition, the production equipment, tooling, and inventory are considered part of capital. Capital outlays for land and buildings can often be reduced by obtaining community involvement in financing. Also, many communities have facilities available at attractive rates for companies that will bring in jobs. While many of these areas are remote and do not have a skilled job pool, there are usually balancing advantages, such as a good work ethic, low overall costs in the area, and state-funded worker training. By starting with a set of clearly-defined requirements, a start-up production operation can properly weigh these alternatives and opportunities in choosing its location.

4.1.2 Production Preparations

After completion of the prototype AHRS, the design must be readied for production. Considerable engineering effort will be required to adapt the design to production equipment, available components, and certification standards. Complete engineering drawings and specifications are needed by Purchasing, Tooling, and Manufacturing to complete their part of the production preparations.

TSO approval is required for the AHRS. The manufacturer will need a small number of prototypes that are fully conformed to the production configuration for extensive testing. Test facilities and equipment will be needed to complete these tests. In many cases, test costs can be controlled by using contract laboratories to perform the tests that require the most expensive equipment.

Supplier/vendor arrangements are critical for the success of the AHRS. Depending upon the design, purchased components could include:

a) Case
b) Mounting Hardware
c) Power Supply System
d) Battery backup
e) Custom Printed Circuit Boards
f) GPS Receiver Engine
g) GPS Antennas
h) Solid-State Rate Gyros
i) Solid State Accelerometers
j) CPU and Memory System
k) Video Driver System and LCD Display if developing a stand-alone system
l) Connectors
m) Cabling, internal and external
n) Switches
o) Miscellaneous electronic hardware
p) Vendor GPS and Video Software or Firmware to RTCA DO-178B Standards
q) Other Software to RTCA DO-178B Standards

While not all-inclusive, this list suggests the scope of effort that will be required to establish formal vendor relationships and prepare contracts and subcontracts to support production.

4.1.2.1 Production Tooling and Setup

Manufacturing planning and tool design are carried out in concert with the product design. Tooling includes any fixtures required for production, special production test tools, and software for automated production equipment and for generating production firmware.

Manufacturing set-up involves the physical placement of the production tooling and equipment, as well as test equipment to be used by Manufacturing and Quality Assurance.

4.1.2.2 Establishing a Quality System

A quality system must be established to provide verification and documentation of the TSO status of each production unit. In its simplest form, a quality system provides stepwise inspections and record-keeping to document that a unit's configuration meets the Technical Standard Order. More sophisticated quality systems also include the use of statistical process controls to reduce the number of post-process inspections that lead to rejections and costly disposition activities.

4.1.3 Manufacturing Operations

The actual production activity includes direct labor involved in building the AHRS and the indirect labor that supports those who do the parts fabrication, subassembly, and final assembly.

A fact of life in modern manufacturing, especially in those companies with complex products and extensive automation is that indirect effort exceeds direct labor by a factor of roughly 3 to 4. The following list identifies some of the functions performed by indirect labor.

- Master Scheduling
- Manufacturing Information Systems
- Manufacturing Planning
- Industrial Engineering
- Configuration Management
- Shipping and Receiving
- Material Transportation
- Inventory Control (Stockrooms)
- Plant and Equipment Maintenance
- Shop Supervision

4.1.4 Marketing

Establishing a Product Marketing capability includes the development of a sales organization, preparation of advertising materials, and attendance at key trade shows.

4.1.5 Product Support

Product Support is often part of the sales organization because both sales and support interface with the customers. The support function distributes Service and Parts Manuals, issues Service Letters, provides Field Representatives, and administers warranty activity.

4.1.6 Other Functions

A number of functions support the overall company effort in diverse ways. Often categorized as "G&A" (general and administrative), these functions include Personnel, Training, Payroll, General Accounting, Legal, and Liability.

4.2 Production Start-Up Through Partnering With Or Licensing To An Established Manufacturer

The cost of creating an AHRS production capability along the lines summarized above is estimated to be between six and twelve million dollars and involves considerable risk. Rather than take this approach, the AHRS developers may choose to align themselves with existing manufacturers who would have start-up cost of between $250K and $750K dollars. Numerous alternatives exist, ranging from licensing to outright sale of the design.

It is assumed that a partnering or licensing arrangement would align production risk with the risk associated with the manufacturer, as shown in Table 4-1. Consequently, in terms of production risk, having the design built by a large, established manufacturer makes the production risk very low. Similarly, a licensing or partnering arrangement with a small avionics manufacturer would involve medium risk.

5. Conclusions

The probability of a TSO-Certified, low-cost AHRS becoming available that is capable of supporting the New and Fully Digital Aircraft markets in the required time frame appears quite high. This reports concludes that the introductory price of a low-cost AHRS cannot far exceed $9K to be a viable product in the defined markets, and that the price must decay to at least the $3-$5K range with an increase in capability by the 2020 time frame.

The projected market for low-cost AHRS is estimated to be sufficient to provide the incentive for some manufacturers to enter the market and make a profit. For manufacturers entering the market for the long-term (through 2020), a profit of approximately 23% is estimated. However, depending upon the manufacturer's capabilities to produce an AHRS, the profit must be adjusted accordingly. The estimated profit of 23% is reasonably accurate for an established manufacturer making higher-cost AHRS and other similar products. The profit would have to be adjusted downward for other less capable manufacturers contemplating the production of a certified AHRS.

Several low-cost TSO-certified AHRS designs are projected to enter the market within the year, some supported by the NASA SBIR program, some from academia and others from industry alone. One of the NASA-sponsored AHRS appears poised to enter the production market in TSO-certified form in 1999 (Seagull Technologies, Inc.). At least two AHRS (Watson Industries AHRS-BA303 and Archangel AHRS) from the kit plane market will gain TSO-certification in 1999, one with a projected single unit price of about $10K. Several promising designs are also on the horizon which probably require venture capital or other similar funding or partnering with an established manufacturer to bring the certified AHRS to market (Vision Micro Design, Orion Dynamics and Control, and EPSCoR (Kansas State University)).

Appendix A - FAA Data Table

FAA Data Table

TABLE 8.1
ACTIVE GENERAL AVIATION AIRCRAFT BY AIRCRAFT TYPE AND PRIMARY USE
1996
Excludes Commuters
(Percent standard error is shown in parenthesis)

Aircraft Type	Total	Public	Corporate	Business	Personal	Instructional	Aerial Application	Aerial Observation	External Load	Other Work	Sight Seeing	Air Tours	Air Taxi	Other
FIXED-WING	**160,577**	**2,827**	**8,227**	**26,963**	**93,174**	**13,248**	**4,653**	**2,519**	**0**	**920**	**408**	**67**	**3,194**	**4,372**
	(0.7%)	(12.4%)	(4.3%)	(3.5%)	(1.3%)	(5.7%)	(3.4%)	(13.8%)	*	(21.8%)	(33.1%)	(85.2%)	(8.6%)	(9.7%)
Piston	**150,980**	**2,285**	**2,549**	**26,043**	**92,715**	**13,149**	**4,275**	**2,481**	**0**	**851**	**408**	**67**	**2,057**	**4,094**
	(0.7%)	(14.7%)	(11.6%)	(3.5%)	(1.3%)	(5.8%)	(3.7%)	(13.9%)	*	(23.2%)	(33.1%)	(85.2%)	(11.7%)	(10.3%)
One Engine	135,244	1,887	1,174	20,796	87,407	12,194	4,135	2,276	0	848	379	48	462	3,632
	(0.7%)	(16.9%)	(18.6%)	(4.1%)	(1.3%)	(6.1%)	(3.5%)	(14.9%)	*	(23.3%)	(34.5%)	*	(30.5%)	(11.1%)
Two Engine	15,678	397	1,364	5,246	5,295	952	130	204	0	3	28	18	1,585	449
	(2.4%)	(26.2%)	(14.5%)	(6.4%)	(6.2%)	(15.6%)	(47.2%)	(30.2%)	(0.0%)	*	*	*	(12.3%)	(25.2%)
Other Piston	57	0	10	0	11	2	9	0	0	0	0	0	9	12
	(48.1%)	(0.0%)	(87.1%)	(0.0%)	(82.1%)	*	(92.2%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(92.2%)	(81.1%)
Turboprop	**5,309**	**451**	**2,327**	**708**	**364**	**73**	**377**	**38**	**0**	**68**	**0**	**0**	**743**	**156**
	(2.5%)	(21.4%)	(7.0%)	(15.8%)	(22.3%)	(56.4%)	(6.4%)	(76.0%)	(0.0%)	(50.0%)	(0.0%)	0	(14.9%)	(37.7%)
One Engine	682	7	41	106	55	17	293	10	0	9	0	0	93	47
	(6.2%)	*	(47.7%)	(25.9%)	(48.3%)	(49.9%)	(6.4%)	*	(0.0%)	(91.6%)	(0.0%)	(0.0%)	(39.3%)	(66.3%)
Two Engine	4,551	443	2,285	602	309	53	11	28	0	59	0	0	649	108
	(2.8%)	(21.7%)	(7.0%)	(18.0%)	(24.8%)	(74.0%)	*	(85.6%)	(0.0%)	(56.0%)	(0.0%)	(0.0%)	(16.1%)	(45.7%)
Other Turboprop	75	0	0	0	0	2	73	0	0	0	0	0	0	0
	(24.1%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	*	(12.8%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)
Turbojet	**4,287**	**89**	**3,350**	**211**	**94**	**25**	**0**	**0**	**0**	**0**	**0**	**0**	**393**	**122**
	(2.3%)	(48.9%)	(3.4%)	(33.8%)	(48.1%)	(75.8%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(17.8%)	(27.0%)
Two Engine	3,971	82	3,098	211	94	25	0	0	0	0	0	0	393	67
	(2.5%)	(53.0%)	(3.7%)	(33.9%)	(48.1%)	(75.8%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(17.8%)	(44.6%)
Other Turbojet	315	7	252	0	0	0	0	0	0	0	0	0	0	54
	(6.6%)	(84.1%)	(6.0%)	*	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(24.8%)
ROTORCRAFT	**6,391**	**1,324**	**868**	**463**	**482**	**487**	**510**	**633**	**357**	**102**	**204**	**54**	**500**	**402**
	(3.4%)	(17.2%)	(22.9%)	(33.7%)	(27.5%)	(26.7%)	(30.0%)	(27.3%)	(30.6%)	(53.1%)	(55.7%)	*	(30.1%)	(30.2%)
Piston	2,415	229	23	172	350	398	312	387	34	71	124	0	26	285
	(6.4%)	(30.3%)	*	(40.7%)	(30.5%)	(25.2%)	(34.1%)	(34.6%)	*	(57.5%)	(70.8%)	(0.0%)	*	(38.6%)
Turbine-total	3,976	1,094	845	290	132	89	198	245	323	31	80	54	473	117
	(3.8%)	(19.9%)	(23.2%)	(47.9%)	(59.3%)	(92.9%)	(55.6%)	(44.5%)	(31.8%)	*	(90.0%)	*	(30.8%)	(44.5%)
One Engine	3,329	994	656	267	124	88	184	239	307	30	77	54	272	31
	(4.2%)	(21.6%)	(29.3%)	(51.6%)	(62.2%)	(94.3%)	(59.3%)	(45.4%)	(33.0%)	*	(93.3%)	*	(51.8%)	*
Multi-engine	646	99	189	23	7	1	14	5	15	0	3	0	200	85
	(9.0%)	(31.6%)	(19.9%)	(75.4%)	*	*	*	*	*	*	*	(0.0%)	(18.5%)	(32.6%)
OTHER AIRCRAFT	**4,144**	**24**	**13**	**21**	**3,247**	**255**	**0**	**3**	**0**	**79**	**216**	**3**	**0**	**279**
	(5.5%)	(80.8%)	*	(76.9%)	(3.6%)	(25.7%)	(0.0%)	*	(0.0%)	(52.2%)	(29.6%)	*	*	(26.1%)
Gliders	1,882	24	0	8	1,469	176	0	0	0	2	33	0	0	167
	(4.5%)	(81.0%)	(0.0%)	*	(5.2%)	(30.0%)	(0.0%)	(0.0%)	(0.0%)	*	(71.4%)	*	(0.0%)	(33.5%)
Lighter-than-Air	2,261	0	13	13	1,777	79	0	3	0	76	183	3	0	111
	(9.4%)	(0.0%)	*	(85.4%)	(5.0%)	(49.2%)	(0.0%)	*	(0.0%)	(53.4%)	(32.5%)	*	*	(41.7%)
EXPERIMENTAL	**16,198**	**30**	**176**	**788**	**12,715**	**270**	**197**	**69**	**66**	**17**	**60**	**0**	**143**	**1,663**
	(4.1%)	(47.7%)	(20.5%)	(21.3%)	(2.7%)	(39.8%)	(42.1%)	(42.1%)	(82.3%)	*	(98.8%)	(0.0%)	(32.4%)	(17.2%)
Amateur Built	11,231	0	0	362	9,618	151	0	3	0	0	54	0	0	1,040
	(5.6%)	(0.0%)	(0.0%)	(40.9%)	(3.1%)	(63.9%)	(0.0%)	*	(0.0%)	(0.0%)	*	(0.0%)	(0.0%)	(23.4%)
Exhibition	2,057	0	0	84	1,437	9	0	0	0	0	4	0	0	521
	(8.6%)	(0.0%)	(0.0%)	(55.2%)	(9.6%)	(79.8%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	*	(0.0%)	(0.0%)	(26.3%)
Other	2,909	30	176	340	1,659	108	197	66	66	17	1	0	143	101
	(4.2%)	(47.7%)	(20.5%)	(18.2%)	(7.0%)	(42.4%)	(42.1%)	(38.0%)	(82.3%)	*	*	(0.0%)	(32.4%)	(62.2%)
ALL AIRCRAFT	**187,312**	**4,206**	**9,286**	**28,236**	**109,619**	**14,261**	**5,361**	**3,225**	**424**	**1,118**	**889**	**125**	**3,838**	**6,718**
	(7.0%)	(10.0%)	(4.4%)	(3.4%)	(1.2%)	(5.5%)	(4.4%)	(12.0%)	(28.8%)	(19.0%)	(22.2%)	(63.9%)	(8.2%)	(7.9%)

* Standard error greater than 100%

NOTE: Columns may not add to totals due to rounding and estimation procedures.

Appendix B - AHRS Information Sheet

Optimal Solutions

Attitude and Heading Reference System (AHRS) Retrofit Information
EAA - Oshkosh 1998

Definition: Retrofit Aircraft Market - Any existing airplane that could benefit from a standalone, secondary source of attitude and magnetic heading information

Description of Retrofit AHRS Functions

AHRS Function	Description
Pitch Attitude	Angle of aircraft's longitudinal axis relative to the earth local level plane located at the aircraft's body axis origin. Pitch Attitude information is displayed to the pilot and may be used by the autopilot and display symbology control laws.
Roll Attitude	Angle of aircraft's lateral axis relative to the earth local level plane located at the aircraft's body axis origin. Roll Attitude information is displayed to the pilot and may be used by the autopilot and display symbology control laws.
True Heading	Angle of aircraft's longitudinal axis projection in the earth local level plane located at the aircraft's axis origin, relative to the True North vector projection into the same earth local level plane. True Heading is undefined at ±90-degree pitch angles. True Heading may be displayed to the pilot in certain modes and may be used by the autopilot or flight management system.

Proposed Standards-Based Performance for AHRS Functions in Retrofit Aircraft Market

Function	Performance Requirement	Standard
Attitude (pitch and bank)	Error < 3° after 180° standard rate turn, Steady State error <1°	TSO-C4c & SAE 8001
Magnetic Heading	±2° Magnetic Compensated	TSO-C6d & SAE 8013A

AHRS Retrofit Aircraft Market, Configurations and Performance Summary

Retrofit Market	Cockpit Configuration	AHRS Configuration	Performance Capabilities	Regulatory Considerations
Existing FAR 23 / 91 aircraft that could use a secondary, self contained source of attitude and heading	• Round dial attitude indicator -vacuum or electric • Magnetic or stabilized compass	Self-contained AHRS and Display • Lowest cost • Minimum outputs to display attitude and heading only (pitch, bank, and true heading) • Requires panel space for the display, space for the sensor unit and power.	• TSO C4c & SAE AS 8001 • Refer Above Table • Portions of ARINC 705	• Secondary system • AC 23.1309-1C Draft • RTCA DO-170B • RTCA DO-160C

Appendix C - Owners Survey

Optimal Solutions

Aircraft Owners
Attitude and Heading Reference System (AHRS) Retrofit Survey
EAA - Oshkosh 1998

Please check your answer to each question in the appropriate box.

7. What share of the airplane do you own?

1☐ Less than 20%
2☐ 20% - 40%
3☐ 40% - 60%
4☐ 60% - 80%
5☐ 80% - 99%
6☐ 100% - FULL OWNER

8. What type of airplane do you own?

1☐ Turbo jet
2☐ Turbo prop
3☐ Multi-engine piston
4☐ Single-engine piston

9. Approximately how much money do you spend annually on your airplane, including flying, maintenance, storage, fuel, repairs, insurance, etc.?

1☐ More than $20,000
2☐ $15,000-$20,000
3☐ $10,000-$15,000
4☐ $5,000-$10,000
5☐ Less than $5,000

10. How many AHRS do you currently have in your airplane?

1☐ Zero
2☐ One
3☐ Two

11. Does you airplane contain any retrofitted avionics equipment?

1☐ Yes
2☐ No

12. Would you consider retrofitting your current airplane to take advantage of a standalone, secondary source of attitude and magnetic heading information?

1☐ Yes
2☐ No

➔ **(Please answer the additional questions on the reverse side)** ➔

13. **What would you expect the described AHRS to cost?**

1☐ Less than $2,000
2☐ $2,000
3☐ $3,000
4☐ $4,000
5☐ $5,000
6☐ $6,000
7☐ $7,000
8☐ More than $7,000

14. **What is the likelihood that you would purchase the described AHRS for the expected cost you gave in question 7?**

1☐ Less than 20%
2☐ 20%
3☐ 40%
4☐ 60%
5☐ 80%
6☐ More than 80%

15. **We would like to contact you by e-mail in case we have follow-up questions. If this is acceptable, then please enter your e-mail address below. We will not distribute it to anyone else**

email address: ______________________________

16. **If you would like to receive information about retrofitting your airplane with a secondary AHRS, please give us your name, address and phone number. We will send you the requested information as soon as it becomes available**

Name: ______________________________

Address: ______________________________

City: ______________________________

State: ______________________________

Country: ______________________________

Zip Code: ______________________________

Phone Number: ______________________________

Appendix D - Forecast Statistics

Forecast Statistics

Following are definitions for the statistics: Trials, Mean, Median, Mode, Standard Deviation, Variance, Skewness, Kurtosis, Coefficient of Variability, Range, and Mean Standard Error.

Trials

The trials are the total number of values that have been generated during the simulation.

Mean

The mean, or average, of a set of values is found by adding them together and dividing their sum by the number of values. 5.2 is the mean of 1, 3, 6, 7, and 9.

Median

The median is the middle value in a set of values. 7 is the median of 1, 3, 7, 8, and 9.

Mode

The mode is the value that occurs most frequently in a set of values. The mode wage, for example, is the one received by the greatest number of workers. If no value occurs more frequently than others, the mode is undefined and is shown as: ---.

Standard Deviation

The standard deviation is the square root of the variance, useful for describing the average deviation.

Variance

Variance is a measure of the spread of a set of values around the mean. When values are close to the mean, the variance is small. When values are widely scattered about the mean, the variance is large.

Skewness

A distribution is said to be skewed if most of the values occur at one end of the range or the other. A positive skewness indicates that most of the values are grouped towards the lower end of the distribution whereas a negative skewness indicates that most of the values are grouped towards the higher end. A skewness of zero means that the distribution is perfectly symmetrical.

Kurtosis

Kurtosis refers to the peakedness of a distribution. For example, a distribution of values may be perfectly symmetrical but look very peaked or flat. A distribution that is fairly peaked might have a kurtosis around 4. A distribution that is fairly flat might have a kurtosis of 2. A normal distribution has a kurtosis of 3.

Coefficient of Variability

This statistic provides an absolute measurement of the variance of a forecast. Since this statistic is independent of the units of a forecast, you can use it to compare the variability of two or more forecasts, even when the forecast units are different.

The Coefficient of Variability typically ranges in value between 0 to 1. It may exceed 1 in a small number of cases in which the variance of the forecast is unusually high.

Range

The range width is the difference between the largest and the smallest numbers in a set of values. The range minimum is the smallest number in the set and the range maximum is the largest number in the set.

Mean Standard Error

This statistic lets you estimate the accuracy of your simulation results and determine how many trials are necessary to ensure an acceptable level of error. It shows the probability of the true mean deviating from the estimated mean by more than a specific amount. The probability that the true mean of the model is within the estimated mean plus or minus the mean standard error is approximately 68%.

Appendix E – Low-Cost AHRS Cost Model

Estimating the Total Number of AHRS Sold Each Year

	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
13	Year	Least	Most Likely	Most	Simulated Purchase Price of AHRS	Probability of Retro/NEW Purchase	Number of Retro A/C who Purchase	Number of SE Aircraft Left w/o AHRS	Attrition on the Current (1996) Fleet	Total Number of AHRS Sold to the Fleet	Number of New Aircraft Pessimistic	Number of New Aircraft Most Likely	Number of New Aircraft Optimistic	Number of New Aircraft Simulated	Number of FDA Aircraft Pessimistic	Number of FDA Aircraft Most Likely	Number of FDA Aircraft Optimistic	Number of FDA Aircraft Simulated	Number of New A/C and FDA who Purchase (assume all FDA)	Number of Retrofit, New A/C and FDA who Purchase Each Year
14																				
15	2001	9000	9000	9000	$9,000	0.0001	10	124927	124927	10	1708	1922	2135	1997					0	10
16	2002	6980	7856	8492	$7,708	0.0125	1532	123023	123033	1542	2022	2275	2528	2387					30	1562
17	2003	6015	7255	8208	$7,099	0.0158	1888	119651	121193	3430	2368	2664	2960	2486					39	1927
18	2004	5413	6857	8012	$6,838	0.0158	1833	115977	119407	5263	2745	3089	3432	3184					50	1883
19	2005	4988	6563	7863	$5,454	0.0220	2472	112410	117673	7735	3156	3551	3946	3822					84	2556
20	2006	4665	6332	7744	$6,529	0.0158	1707	108257	115992	9442	3603	4054	4504	3986					63	1770
21	2007	4409	6144	7644	$5,626	0.0199	2089	104919	114361	11531	4088	4599	5110	4465					89	2178
22	2008	4198	5985	7559	$5,742	0.0188	1848	98256	109787	13379	4037	4542	5047	4580	108	360	721	414	500	2348
23	2009	4021	5848	7485	$5,529	0.0210	1934	92016	105395	15313	3889	4375	4861	4396	243	810	1620	840	932	2866
24	2010	3868	5728	7419	$6,091	0.0167	1429	85867	101180	16742	3628	4082	4535	4376	408	1361	2721	1350	1423	2852
25	2011	3735	5622	7360	$5,956	0.0173	1390	80390	97132	18132	3239	3644	4049	3584	607	2025	4049	1928	1990	3380
26	2012	3618	5527	7306	$5,030	0.0299	2243	75115	93247	20375	2704	3042	3380	2813	845	2817	5634	3294	3378	5621
27	2013	3513	5441	7258	$5,202	0.0261	1807	69142	89517	22182	2002	2252	2503	2056	1126	3754	7508	3561	3615	5422
28	2014	3419	5362	7213	$4,925	0.0326	2075	63755	85937	24257	1110	1248	1387	1290	1456	4855	9709	4195	4237	6312
29	2015	3334	5290	7171	$5,180	0.0266	1547	58242	82499	25804	0	0	0		1842	6139	12279	5470	5470	7017
30	2016	3256	5224	7132	$4,998	0.0307	1636	53395	79199	27440					2035	6784	13568	6308	6308	7944
31	2017	3184	5162	7096	$4,936	0.0323	1567	48591	76031	29007					2246	7487	14974	7236	7236	8803
32	2018	3118	5104	7062	$4,619	0.0423	1861	43983	72990	30868					2476	8253	16507	9731	9731	11592
33	2019	3057	5051	7030	$4,508	0.0466	1827	39202	70070	32695					2727	9089	18178	10062	10062	11889
34	2020	3000	5000	7000	$4,673	0.0404	1395	34572	67267	34090					3000	10000	20000	10381	10381	11776

This spreadsheet models the uncertainty in the price of the AHRS, number of NEW aircraft, and the number of FDA aircraft to obtain an estimate of the total number of aircraft each year that purchase an AHRS. Note that the rows from 15 - 34 represent the years from 2001 to 2020.

To calculate the total number of aircraft each year that purchase an AHRS, the number of existing fleet aircraft that Retrofit the AHRS, the number of NEW aircraft that install the AHRS, and the number of FDA that install the AHRS must be estimated and then added to find the total AHRS sold each year. Note that this is one iteration of the spreadsheet model from the 5,000 iterations that comprise the simulation model.

To calculate the number of Retrofit and NEW aircraft that purchase an AHRS each year, a price is determined from the triangular distribution of the price-decay curves. Column F, G & H give the triangular distribution of the price-decay curves. Note that the Least ("Optimistic") curve decays to $3,000, the Most Likely decays to $5,000, and the Most ("Pessimistic") decays to $7,000. Column I values are chosen by Crystal Ball according to the associated row triangular distribution of the price-decay curve. (Each value in Column I will be between the "Least" and "Most" values with highest probability of being close to the Most Likely value. Column J is the calculated value of the probability of purchase based upon the simulated price in column I. Column K is the number of single engine aircraft that purchase a retrofit AHRS found by taking the row value in column J times the associated row value in column L. (Column L values are calculated after considering the associated row values in columns M & N. Columns O, P, & Q represent the triangular distributions associated with the introduction of the NEW aircraft and column R is the value chosen by Crystal Ball from this distribution. The number of NEW aircraft that purchase an AHRS each year is determined by the probability value given in column J times the NEW aircraft value in column R.

Columns S, T, & U are the triangular distributions associated with the introduction of the FDA. Column V contains the value chosen by Crystal Ball according to the FDA distribution. Column W is determined by adding column K and column R times column J and represents the total number of AHRS sold each year to the New and FDA market. Column X is the total AHRS sales, Retrofit, NEW and FDA, by year.

Estimating the Net Profit From the Sale of AHRS for 20-years

	X	Y	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
13	Number of Retrofit, New A/C and AGATE who Purchase Each Year	Cumulative Retrofit, New, & AGATE Who Purchase	Revenue Generate by AHRS Sales in All Markets	Cumulative Revenue	Total Pre-Invest Profit	Pre-Invest Profit per Manufacturer	Cumulative Profit per Manf.	R&D Cost	Certification Cost	Cumulative Investment	Cum. Net Profit	Year
14												
15	10	10	$91,554	$91,554	$22,889	$5,722	$5,722	1000000	1000000	2000000	-$1,994,278	2001
16	1562	1572	$12,037,193	$12,128,747	$3,009,298	$752,325	$758,047			2000000	-$1,241,953	2002
17	1927	3499	$13,681,447	$25,810,194	$3,420,362	$855,090	$1,613,137			2000000	-$386,863	2003
18	1883	5382	$12,863,220	$38,673,414	$3,215,805	$803,951	$2,417,088			2000000	$417,088	2004
19	2556	7939	$13,940,693	$52,614,107	$3,485,173	$871,293	$3,288,382			2000000	$1,288,382	2005
20	1770	9708	$11,555,528	$64,169,635	$2,888,882	$722,221	$4,010,602			2000000	$2,010,602	2006
21	2178	11886	$12,252,962	$76,422,597	$3,063,241	$765,810	$4,776,412	500000		2500000	$2,276,412	2007
22	2348	14234	$13,482,175	$89,904,773	$3,370,544	$842,636	$5,619,048		1000000	3500000	$2,119,048	2008
23	2866	17101	$15,847,248	$105,752,021	$3,961,812	$990,453	$6,609,501			3500000	$3,109,501	2009
24	2852	19953	$17,370,738	$123,122,759	$4,342,684	$1,085,671	$7,695,172			3500000	$4,195,172	2010
25	3380	23333	$20,131,275	$143,254,034	$5,032,819	$1,258,205	$8,953,377			3500000	$5,453,377	2011
26	5621	28954	$28,273,762	$171,527,796	$7,068,440	$1,767,110	$10,720,487			3500000	$7,220,487	2012
27	5422	34376	$28,203,940	$199,731,736	$7,050,985	$1,762,746	$12,483,234			3500000	$8,983,234	2013
28	6312	40687	$31,086,014	$230,817,750	$7,771,503	$1,942,876	$14,426,109			3500000	$10,926,109	2014
29	7017	47704	$36,348,060	$267,165,810	$9,087,015	$2,271,754	$16,697,863			3500000	$13,197,863	2015
30	7944	55648	$39,704,112	$306,869,922	$9,926,028	$2,481,507	$19,179,370			3500000	$15,679,370	2016
31	8803	64451	$43,451,608	$350,321,530	$10,862,902	$2,715,726	$21,895,096			3500000	$18,395,096	2017
32	11592	76043	$53,543,448	$403,864,978	$13,385,862	$3,346,466	$25,241,561			3500000	$21,741,561	2018
33	11889	87932	$53,595,612	$457,460,590	$13,398,903	$3,349,726	$28,591,287			3500000	$25,091,287	2019
34	11776	99708	$55,029,248	$512,489,838	$13,757,312	$3,439,328	$32,030,615			3500000	$28,530,615	2020
35												
36									Total Rev. per Manf.		$128,122,459	
37									Total Profit per Manf.		$28,530,615	
38									Net Profit		22.27%	

This spreadsheet is a continuation of the number of AHRS sold by year model, the results of which are found in column X. Note that the rows 15 - 34 represent the years as displayed in column AJ. Column Y is the cumulative number of AHRS sold. Column AA is the revenue generated by the number of AHRS sold at the price found in Column I . Column AB is the cumulative revenue by year. Column AC is the pre-investment (without R&D and Certification Cost) profit at 25% of the revenue. Column AD & AE are the profit and cumulative profit per manufacturer, respectively, with the assumption of 4 manufacturers. Columns AF and AG give the R&D cost and the certification cost in the year they occur. Column AH is the cumulative investment in R&D and certification and column AI is the cumulative net profit. Cell AI 36 is the total revenue per manufacturer found by dividing AB 34 by 4. Cell AI 37is the total profit per manufacturer. The manufacturer net profit is found in cell AI 38 and is calculated by dividing cell AI 37 by cell AI 36.

This spreadsheet is one iteration of the simulation that captures the uncertainty in the net profit estimate induced by the uncertainty in the inputs to the model. The 5,000 numbers that appear in cell AI 38 during the 5,000 iterations of the model are captured and displayed as a distribution in market assessment in the chart titled, “Probable Profit over the 20-Year Period.

Estimating the Minimum Baseline of NEW & FDA to Achieve 20% Net Profit

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	R	S	T
1														Number of				
2								Percent:	0.15			Pre-Invest Profit:	0.25	Manf.				
3														4				
4	Year	Price	Probability of Purchase	Number Sold to Retrofit	NEW & FDA A/C	Percent Times New/FDA	FDA A/C	New A/C	New A/C That Buy	FDA A/C That Buy	Total Revenue	Cumulative Revenue	Total Pre-Invest Profit	Pre-Invest Profit per Manufactur	Cumulative Profit per Manf.	Cumulative Investment	Cum. Net Profit per Manf	
5																		
6	2001	9000	0.0001	10	2135	320		320	0		$90,000	$90,000	$22,500	$5,625	$5,625	2000000	-$1,994,375	-$7,977,500
7	2002	7856	0.0106	1302	2528	379		379	4		$10,259,382	$10,349,382	$2,564,845	$641,211	$646,836	2000000	-$1,353,164	-$5,412,655
8	2003	7255	0.0155	1859	2960	444		444	7		$13,530,266	$23,879,648	$3,382,566	$845,642	$1,492,478	2000000	-$507,522	-$2,030,088
9	2004	6857	0.0158	1838	3432	515		515	8		$12,657,421	$36,537,068	$3,164,355	$791,089	$2,283,567	2000000	$283,567	$1,134,267
10	2005	6563	0.0158	1776	3946	592		592	9		$11,714,863	$48,251,931	$2,928,716	$732,179	$3,015,746	2000000	$1,015,746	$4,062,983
11	2006	6332	0.0160	1744	4504	676		676	11		$11,106,893	$59,358,825	$2,776,723	$694,181	$3,709,927	2000000	$1,709,927	$6,839,706
12	2007	6144	0.0165	1741	5110	767		767	13		$10,769,844	$70,128,669	$2,692,461	$673,115	$4,383,042	2500000	$1,883,042	$7,532,167
13	2008	5985	0.0171	1705	5768	865	108	757	13	108	$10,928,229	$81,056,898	$2,732,057	$683,014	$5,066,056	3500000	$1,566,056	$6,264,224
14	2009	5848	0.0180	1679	6481	972	243	729	13	243	$11,316,013	$92,372,911	$2,829,003	$707,251	$5,773,307	3500000	$2,273,307	$9,093,228
15	2010	5728	0.0189	1656	7256	1088	408	680	13	408	$11,897,919	$104,270,830	$2,974,480	$743,620	$6,516,927	3500000	$3,016,927	$12,067,708
16	2011	5622	0.0200	1632	8098	1215	607	607	12	607	$12,655,765	$116,926,596	$3,163,941	$790,985	$7,307,912	3500000	$3,807,912	$15,231,649
17	2012	5527	0.0210	1605	9014	1352	845	507	11	845	$13,596,703	$130,523,299	$3,399,176	$849,794	$8,157,706	3500000	$4,657,706	$18,630,825
18	2013	5441	0.0222	1573	10011	1502	1126	375	8	1126	$14,728,759	$145,252,058	$3,682,190	$920,547	$9,078,254	3500000	$5,578,254	$22,313,014
19	2014	5362	0.0233	1535	11096	1664	1456	208	5	1456	$16,065,891	$161,317,949	$4,016,473	$1,004,118	$10,082,372	3500000	$6,582,372	$26,329,487
20	2015	5290	0.0245	1492	12279	1842	1842	0	0	1842	$17,632,719	$178,950,668	$4,408,180	$1,102,045	$11,184,417	3500000	$7,684,417	$30,737,667
21	2016	5224	0.0257	1441	13568	2035	2035			2035	$18,157,845	$197,108,513	$4,539,461	$1,134,865	$12,319,282	3500000	$8,819,282	$35,277,128
22	2017	5162	0.0269	1385	14974	2246	2246			2246	$18,743,247	$215,851,760	$4,685,812	$1,171,453	$13,490,735	3500000	$9,990,735	$39,962,940
23	2018	5104	0.0282	1323	16507	2476	2476			2476	$19,386,658	$235,238,418	$4,846,665	$1,211,666	$14,702,401	3500000	$11,202,401	$44,809,604
24	2019	5051	0.0294	1256	18178	2727	2727			2727	$20,111,389	$255,349,807	$5,027,847	$1,256,962	$15,959,363	3500000	$12,459,363	$49,837,452
25	2020	5000	0.0306	1184	20000	3000	3000			3000	$20,915,000	$276,264,807	$5,228,750	$1,307,188	$17,266,550	3500000	$13,766,550	$55,066,202
26																		
27																Total Rev. per Manf.		$69,066,202
28																Total Profit per Manf.		$13,766,550
29																Net Profit		20%

This spreadsheet contains the model used to estimate the number of FDA and NEW aircraft, in addition to the Retrofit of existing fleet aircraft with an AHRS, needed each year to yield a Net Profit of 20% to the manufacturer of the AHRS.

The only variable in this model is the percent of the optimistic NEW/FDA production curve needed to achieve 20% net profit. This variable is found in Cell I 2 and is listed as 15%. Increasing or decreasing this number will have a similar effect on the net profit value found in Cell T29 which is found by dividing T28 by T27.

Column A contains the years from 2001 to 2020. Column B contains the most likely price decay for the AHRS. Column C contains the probability of purchase associated with the respective price in Column B. Column D is the number of AHRS sales to the Retrofit market. Column E is the optimistic NEW/FDA production curve. Column F is the percent in Cell I2 times the values in Column E. Columns G & H are the distribution of FDA and NEW aircraft respectively. Column I is the number of NEW aircraft that purchase an AHRS as found by multiplying the column C by column H. Column J is the number of FDA that buy an AHRS. Column K is the total revenue found by multiplying column B by the sum of columns D, I & J. Column L is the cumulative revenue. Column M is the profit before investment in R&D and certification, assumed to be 25% or total revenue and is found by multiplying .25 times column K. Columns N & O are the profit and cumulative profit per manufacture before investment in R&D and certification found by dividing column H by 4 in column N and then summing column N in column O. Column R is the cumulative investment in R&D and certification and columns S & T are the cumulative net profit per manufacturer and the total cumulative net profit.

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Daniel Yuchnovicz, Malcolm Burgess, and William Hammers

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Research Triangle Institute
One Enterprise Parkway, Suite 310
Hampton, VA 23666

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13. ABSTRACT (*Maximum 200 words*)
This report provides an assessment of technical and production risks of candidate low-cost attitude/heading reference systems (AHRS) for use in the Advanced General Aviation Transport Experiments (AGATE) airplanes. A low-cost AHRS is a key component of modern "glass cockpit" flight displays for General Aviation (GA) aircraft. The technical capabilities of several candidate low-cost AHRS were examined and described along with the technical issues involved with using all solid-state components for attitude measurement. An economic model was developed which describes the expected profit, rate of return, and volume requirements for the manufacture of low-cost AHRS for GA aircraft in the 2000 to 2020 time frame. The model is the result of interviews with GA airframe manufacturers, avionics manufacturers and historical analysis of avionics of similar complexity. The model shows that a manufacturer will break even after three years of AHRS production, realizing an 18 percent rate of return (23 percent profit) on an investiment of $3.5M over the 20 year period. A start-up producton estimate showed costs of $6-12M for a new company to build and certify an AHRS from scratch, considered to be a high-risk proposition, versus $0.25-0.75M for an experienced avionics manufacturer to manufacture a design under license, a low-risk proposition.

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